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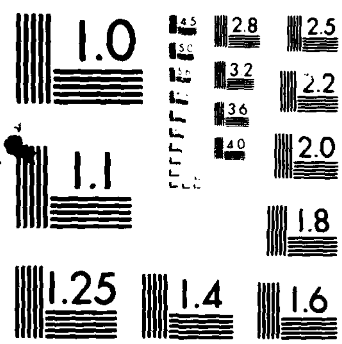

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EFFECT OF A PREDICTOR DISPLAY
ON CARRIER LANDING PERFORMANCE -
PHASE A (DISPLAY DEVELOPMENT)

dea WESTERN DIVISION

Prepared for:

Engineering Psychology Programs
Office of Naval Research
Department of the Navy
Arlington, Virginia 22217

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13. ABSTRACT

This report documents work performed during Phase A of a three-phase program to determine the effect of a predictor display on carrier landing performance.

Phase A was designed to determine predictor display information requirements, to develop an F4 predictor model and one or more effective predictor display mechanizations, and to produce a tentative plan for later conduct of a full-blown experimental evaluation of the predictor concept. Eleven carrier approach information items were identified, nine of which should be provided continuously. Of those nine, two are currently missing in the daytime and four are missing at night. Of the information items currently available, four of the seven daytime and three of the five nighttime items are poor in quality or must be inferred by the pilot from direct information.

Those missing information items are added and the poor quality information items are improved in Dunlap's predictor display design concepts. Most landing information is integrated in the form of two display constructs: a reference glideslope and a fast-time predicted flight path. There are three versions of the display to be evaluated: a side view, a front view with vertical prediction and a front view full motion predictor. Prototype predictor displays have been mechanized and the technical feasibility of the landing predictor has been demonstrated in the Dunlap laboratory and at the Naval Missile Center, Pt. Mugu, California. A novel approach to predicting ship motions was explored and has been found to be promising. General plans for Phases B and C are also provided.

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INTRODUCTION

Carrier landing is a critically difficult task. Aircraft carrier operations, especially at night, are associated with relatively high aircraft accident rates. There are good reasons to believe that a major problem in the carrier landing system is lack of sufficient or sufficiently good landing information afforded to the pilot.

Much research and many studies, some of which were performed by Dunlap and Associates, Inc., (1-8), have been performed on the carrier landing problem over the last 20 years. There have been some progress and a few improvements, but the carrier landing problem is still a formidable one. It continues to be a stressful part of a naval aviator's life and it continues to generate an unacceptable number of accidents, especially at night. More important, the fleet is restricted in the kinds of operational environments during which air and landing operations can be conducted. For example, air operation may be reduced and certain types of aircraft "grounded" at night, during poor atmospheric conditions, or during rough seas. Furthermore, boarding rates typically are low during such conditions.

In parallel to Dunlap's association with the carrier landing problem is its history of involvement with manual control problems, including development of the predictor instrument (9-16). The predictor has been shown to be extraordinarily effective in a variety of complex manual control tasks, yet no attempt has been made to apply it to the carrier landing problem until this study.

The predictor display presents to an operator the predicted future state of one or more variables under his control. It is especially useful in vehicular control. Depending on what the vehicle operator is trying to do and what is actually predicted, the operator can immediately determine what control correction, if any, has to be made to his vehicle, make them if desired, and see what the results will be before they happen. His control is shifted from near the present to the future. Predictive information is generated by a fast time model of the controlled system operating on an accelerated time scale. The model receives signals from sensing instruments that are responsive to existing conditions in the real time system. Those signals form the initial conditions with which the model begins each cycle of accelerated time. The model then computes predictions repetitively of the real time system's future and extrapolates the initial state on its accelerated time scale to generate the instrument's display.

On March 15, 1971 Dunlap and Associates, Inc. in cooperation with the Navy laboratories at Point Mugu, California began the first phase of a three-phase program under contract to the Psychological Sciences Division of the Office of Naval Research. The objective of the program is to determine the effects of a predictor display on carrier landing performance. It is hypothesized that a predictor display can significantly improve the content and display of information available to a pilot during a carrier landing approach, especially at night. With information and display improvements, the pilot should be able to improve his glideslope control and consequently improve his landing performance.

The purpose of this report is to document the results of Phase A of the three-phase program and to provide the general plans for Phases B and C. Phase A was designed to determine predictor display information requirements, to develop an F4 predictor model and one or more effective predictor display mechanizations, and to produce a tentative plan for later conduct of a full-blown experimental evaluation of the predictor concept. Also during Phase A, a novel approach to predicting ship motions was to be explored. The results of that exploration are reported in Section 3 of the Appendix to this report.

Phase B is designed to complete development of the experimental displays, set-up a simulation of the carrier landing problem and other experimental apparatus, and conduct informal comparisons of the displays. The results of informal comparisons will permit dropping one or two displays from further evaluation and provide data for final planning of Phase C.

The purpose of Phase C is to conduct a full simulation experiment including training and running subjects; collecting, reducing and analyzing data; evaluating results and producing a final report. The data should demonstrate the effects of a predictor display on simulated carrier landing performance.

CARRIER LANDING DISPLAY INFORMATION REQUIREMENTS

INTRODUCTION TO DISPLAY REQUIREMENTS STUDY

The first major task in the Carrier Landing Predictor Display study has been concerned with establishing information requirements for the display and identifying the display's interface requirements with its intended operational environments.

It was recognized immediately that three "displays", each with its own operating environment, are involved in the study. The first "display" consisted of simple analog breadboard mechanizations of important display elements and dynamics of the predictor display developed in Dunlap's small laboratory facility. Second there is the "display" set-up which will be used to run evaluation trials and experiments during Phases B and C. This display set-up actually involves more than one display configuration and will operate in the hybrid analog-digital computer environment at Pt. Mutu. Finally there is the prototype display which may someday be installed in an aircraft for flight evaluation. It will not be a product of Phases B or C but rather a product of some subsequent program to follow, assuming positive results are obtained in this evaluation program.

The discussion of the carrier landing problem and display information requirements which follows will apply mostly to the last display i.e., the prototype display which will operate in an aircraft environment. The final prototype display will differ from the experimental displays in the following ways:

- The experimental displays were designed to operate in a laboratory environment rather than in an aircraft environment which will be necessary for the prototype display and which implies different interface requirement.

- The experimental display does not include many complicating information elements necessary to a pilot flying an actual aircraft but unnecessary for experimental purposes.

- The symbology and layout in the experimental display is not as highly developed and optimized as would be desirable in an aircraft prototype display.

- The front view experimental display was not specifically designed to operate as a head-up display (HUD) which later

study could show to be required. However, it is compatible with an HUD treatment.

PILOT CONTROL TASKS IN LANDING ON CARRIERS

The fundamental tasks which a pilot must perform in landing an aircraft on an aircraft carrier are:

- maintain safe flight during the approach
- stay within terminal landing parameters
- hit the touchdown area

Performance of those tasks is complicated by the fact that the ship is underway and that the landing deck is on an offset angle to the direction of ship heading and the relative wind created by ship's motion. The ship's passage through the air also causes air turbulence or "burble" aft of the landing deck. On all carriers, except the nuclear-powered Enterprise, stack gases may interfere with pilot's visibility. Much more serious than those factors are the pitching, rolling, yawing and heaving motions that the landing deck is subject to, especially during rough seas. The deck motions at times increase the effective impact velocity of landing aircraft and at other times reduce hook-to-ramp clearance. The situation becomes perilous when an aircraft is not within glideslope tolerance or within tolerance on one or more of its specified landing parameters. Furthermore, the pilot's task is made more difficult by the lack of heave stabilization in the Fresnel Lens Optical Landing System (FLOLS) which results in some glideslope position error in the FLOLS indications to the pilot. Other problems with the FLOLS are discussed later.

Maintaining Safe Flight

Every aircraft has an optimum approach speed for landing purposes. That speed is a compromise among the airplane's flying qualities, the requirement to maintain safe flight, its response to power application, its cockpit visibility, and the strength limits of the aircraft and its arresting gear. With greater than optimum speed, the aircraft will approach too fast, resulting in decreased time for the pilot to achieve and maintain the proper glideslope and large impact velocities. At slower than optimum speed, the aircraft is on the backside of the power curve (or in the region of reverse command) where speed is unstable with fixed thrust.

Jet aircraft differ from each other in longitudinal static stability, phugoid damping and airspeed - power stability at the relatively slow landing speeds which must be achieved. Aircraft also differ in ratio of power-required to power-available, engine-response and throttle sensitivity. Speed corrections are difficult when flying below optimum approach speed, margins for error are slim, and stall speed is too close. To complicate matters, approach speed must be varied to maintain the same flying qualities at all landing weights. Allowable variations in aircraft weights of 5,000 lbs. are not unusual. To avoid stalls, regardless of gross weight, air density, or bank angle, pilots control their aircraft with respect to angle-of-attack rather than airspeed. The two are directly related for a given set of aircraft and atmospheric conditions. Angle-of-attack is the angle between the chord line of the airfoil and the relative wind. It has nothing to do with the horizon (that's pitch angle).* Angle-of-attack is measured directly on the aircraft with a freely rotating probe located on the airframe where local airflow is relatively undisturbed. The probe seeks alignment with the airstream, and provides an electrical signal of angle-of-attack. Angle-of-attack does not need to be calculated with a computer using sink speed, altitude, position of the horizon, or anything else to which it is only indirectly related.

Angle-of-attack must be controlled within tolerance at all times during the carrier landing approach to maintain safe flight. It can be controlled effectively with the stick while the throttle is used to control altitude. However, with the approach power compensator (APC), angle-of-attack is controlled automatically (within limits) to compensate for the pilot's glideslope corrections with the stick. The APC method of control is assumed for purposes of this study.

Staying Within Terminal Landing Parameters

Because of the high approach speed and sink rate characteristics of jet aircraft, a glideslope within a minimum and maximum glideslope angle (perhaps different for each aircraft type) must be achieved by an aircraft by the time it enters the terminal phase of the approach (i.e., 300' to 700' before the ramp to touchdown). Therefore, the glideslope influences the manner in which the total approach is performed.

Jet aircraft are not "landed" on carriers the way they are on field landing strips or the way that prop aircraft were "landed" on aircraft carriers some years ago. Jet aircraft are "arrested". Their approach speeds must be faster than prop aircraft to maintain airspeed and to

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*Navweps 00-80Q-59

permit a go-around should they bolter. Because of their fast minimum airspeed and lack of time or capability for "flaring", (due to short ramp to #3 wire distances) jet aircraft must be flown-down to the wire to permit an arrestment.

To clear the ramp safely and not bolter while at the same time staying within the specified ranges of landing parameters, the pilot must approach the landing deck at or about the given glideslope angle. If the glideslope from ramp to touchdown is relatively shallow, resulting sink speeds are low. But if the glideslope is too shallow there is danger of either hitting the ramp, especially when the deck is pitching, or of touching-down beyond the wires. If relatively steep glideslopes are followed from ramp to touchdown, clearing the ramp can be easily managed. But if the glideslope is too steep, then a hard landing is likely. So, the all important terminal requirement from ramp to touchdown is a certain optimum glideslope or close to it. If it is achieved early enough in the approach, chances are good for clearing the ramp, hooking a wire, preferable #3, and touching down with an acceptable impact velocity.

Hitting the Touchdown Area

Hitting the touchdown area involves both a vertical and a lateral control problem. The vertical control objective in hitting the touchdown area is transformed because of terminal condition requirements. Theoretically there are a large number of flight paths that a pilot can fly and still hit the target. In fact, current carrier landing performance research indicates that only a small percentage of successful arrestments were achieved by strict maintenance of a given glideslope all the way down from meatball acquisition to touchdown. However, pilots were <u>trying</u> to stay on glideslope and somehow did approximate required terminal conditions. It is unlikely that pilots would do better by ignoring the glideslope.

Because of the terminal condition requirements, the number of possible vertical flight paths which can end up in successful arrestments are restricted because it is difficult to correct for glideslope errors toward the end of the approach <u>without also</u> deviating from required terminal parameters. Difficulties in salvaging a poor approach, approaching high and subsequently diving for the deck, flying up through the glideslope after compensating for a low approach, etc. have been described many times elsewhere. They all indicate that it is very difficult or impossible to correct for glideslope errors late in the approach <u>and also</u> achieve optimal terminal conditions.

That fact seems to be connected with the relation of sink rate to both control objectives. Sink rate is involved with vertical control in hitting the touchdown area and in maintaining terminal conditions. Since forward airspeed must be kept relatively constant in hitting the touchdown area, vertical control is achieved by varying sink rate appropriately with the throttle (or with the stick in APC equipped aircraft). Similarly, in achieving terminal conditions, proper control of sink rate is critical in maintaining the appropriate glideslope and avoiding hard landings. Vertical control necessary for hitting the touchdown area correctly must be performed early in the approach to steady the aircraft on glideslope before the terminal phase occurs. Furthermore the control objective should not be to hit the touchdown area per se, but rather to achieve* and steady-up on the glideslope. Achieving proper glideslope control will accomplish both hitting the touchdown area and the required terminal conditions.

In summary, it would be an oversimplification to view the control problem as merely a tracking or trajectory problem whereby the aircraft's descent is controlled simply to hit a moving target. The control problem is to place the aircraft within certain terminal motion parameters while at the same time hitting the moving target in a situation where both control parameters are cross-coupled. That is why a glideslope reference is so important in carrier landing. It provides a single performance standard which if achieved, satisfies many of the multiple requirements in the situation. It simplifies the control task for the pilot. Of course, the better the control or the control information provided to the pilot the quicker and easier it will be for him to achieve glideslope. On the other hand, it is probably easier to maintain proper glideslope having once achieved it than to achieve it in the first place. Achieving glideslope is possible only if adequate information is made available early in the approach.

Line-up

Line-up involves keeping the aircraft laterally on or close to the glideslope during the approach and lined-up with the centerline of the landing

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*More is implied by "achieving glideslope" than just placing the aircraft in a center position on the glideslope, i.e., achieving center meatball. A pilot can see the centerball while gliding up or down through the glideslope however quickly or slowly, but that only achieves centerball. Achieving glideslope means getting the centerball after setting up a flight path with the appropriate angle-of-attack (i.e., approach speed) and sink rate which very nearly coincides with the reference glideslope set up for that aircraft.)

deck. The line-up task is interconnected with control of roll and yaw while making correcting turns during the approach. It also involves keeping the wings level in the terminal phase of the approach to assure ramp clearance and cancelling out yawing motions to avoid a twisting impact on the plane's arresting gear.

Line-up appears to be relatively less of a control problem than vertical control. That conclusion seems to be indicated by the types of carrier landing accidents which occur. Few aircraft accidents are attributed to lateral error. On the other hand over 90 percent of the carrier landing accidents are due either to hard landings or undershoots -- indications of vertical glideslope error.

However, the difficulty level of a control task is determined at least as much by the quantity and quality of control information as by the nature of the control task itself. It is known that information for lateral control is quite good in present carrier landing systems while information for vertical control is poor. The lateral control task per se may be inherently as difficult as the vertical control task and might appear so if lateral information were as poor as vertical information. On the other hand, vertical control might appear to be as "easy" as lateral control if vertical information were as good as lateral information now is. It might reasonably be expected that vertical control would be much improved if pilots didn't have to spend the time they do on lateral control or if the lateral control task were easier. To an untrained operator trying to "fly" an aircraft in a simulator during a carrier landing, the lateral control task seemed more difficult than the vertical task.

While the lateral control task does not appear to be a "problem" in current carrier landing operations it is not clear that it should be ignored. The eventuality which must be guarded against is any inadvertent increase in the difficulty of the lateral control task which could result from increasing the pilot's scan for landing information or by displaying lateral and vertical control information separately.

APPROACHES TO IMPROVING LANDING INFORMATION

In spite of the difficulty of their tasks and related problems, pilots do surprisingly well in landing aircraft on carriers in the daytime and the current day accident rate is at a reasonable level. However, the accident rate is much higher at night, during poor visibility conditions, and during pitching deck conditions.

There is some controversy as to how to improve the carrier landing situation without making basic aircraft design changes. Two basic solutions

are to try to automate the landing or to simplify the pilot's task by improving his information. The Automatic Carrier Landing System (ACLS) is the current attempt to automate carrier landings. This study is only concerned with the second type of solution.

It would seem that more or better information is available to pilots in the daytime than at night. The primary altitude control information source which pilots are supposed to rely on (the meatball of the FLOLS) is available both day and night. As is discussed later, the FLOLS is marginal and not sufficiently accurate to satisfy the pilot's information needs. Therefore, in the daytime during good visibility conditions, pilots probably take advantage of a number of natural visual cues to help them determine where they are, where they are going, and how to control their aircraft to land safely. It is not clear what percentage of reliance pilots place on the meatball, LSO instructions, or natural visual cues while landing aircraft. It is clear, however, that only the natural visual cues are missing at night.

There are two basic approaches to improving the pilot's landing information: (1) to make "night like day" or (2) to provide better, more accurate, or additional instrument-type information day and night than is currently available. If successful, approach (1) could make night landing performance as good as day. If approach (2) is successful, not only could night landings be as good as day but perhaps day landings could be improved over current day performance levels.

Various carrier floodlighting schemes and the vertical contact analog display are examples of the first approach. The underlying intention with the contact analog display is to simulate and display on a CRT certain selected visual cues which one might actually see and use in the real world under good visibility conditions. The premise is that if the significant aspects of "day" can be reproduced on a display used at night (or in poor visibility conditions) then "night" can be made to look like "day". (The same thing might well be achieved more simply with a low light level TV system for certain situations.) There are difficulties with this approach.

One is that it is difficult to achieve a "head up" configuration with a contact analog. Failure to achieve "head up" requires the pilot to transition back and forth between a "head in the cockpit" and a "head up" mode. This is extremely difficult to perform with a critical task that demands constant attention for a minimum duration of about 30 seconds.

Second, it requires much more research to design a proper dynamic display that attempts to simulate certain aspects of reality than to design

a symbolic or instrument display. With a symbolic display exact and simple error information which a pilot needs to land his aircraft (e.g., vertical error now and in the future) can be computed and given to him directly in a form compatible with his controls without requiring him to make difficult judgements or transformations. With natural visual cues or with a vertical contact analog display a pilot has to extract relevant cues and transform them (on the basis of his long term association with them) to create the information he needs. In a contact analog display, for example, vertical error must be estimated by associating relative sizes of simulated visual cues with some reference in the display.

Another problem with the "make-night-like-day" approach is that the natural visual world is full of sources of visual illusions. Simulated natural cues, if used, at night are likely to be the subjects of the same illusory phenomena as the natural cues themselves are at night.*

The predictor carrier landing display being developed in this study is an example of the alternate approach to improving the pilot's landing information, i.e., to provide a symbolic display with better and more accurate, simple error instrument information about the aircraft's current and/or future position. The FLOLS system, drop lights, proposed new LSO console designs and Compensated Meatball Landing systems, all external to the aircraft, are other examples of the second approach.

DISPLAY INFORMATION REQUIREMENTS

There are two important informational constructs which apply to the carrier landing situation: (1) the reference glideslope and (2) the flight path which the aircraft actually flies. As discussed earlier, the control objective is to make the two coincide.

There are many separate information parameters which can be used to describe either of these two constructs, e.g., range from CVA altitude, sink rate, closing rate, etc. These and other parameters are necessary and useful when analyzing aircraft motions for various research and engineering purposes. They will also be necessary data inputs to predictor equipment to give the display realistic dynamics and characteristics. But the direct display of these many separate parameters to the pilot is not required or advisable. The pilot's internal conceptual model of his aircraft and motions with respect to the glideslope reference is integral. If separate parameters

*A Rationale for Evaluating Visual Landing Aids: Night Carrier Recovery, Dunlap and Associates, Inc., February 1966.

describing the state of this simple and integral concept are displayed, then the pilot is forced to piece the situation together from multiple sources. This is obviously more difficult, time consuming and error prone than if the information is presented in an integrated manner.

The discussion of pilot's information requirements which follows is compatible with the notion of presenting integrated information in the form of dynamic glideslope reference and aircraft flight path line constructs. It is at this conceptual level that the pilot can most easily function and also the level at which the predictor display operates.

The two pieces of information a pilot needs to hit a specified area on the landing deck and also satisfy terminal performance requirements are glideslope reference and deviations from glideslope. Since the glideslope reference incorporates several separate pieces of information, glideslope deviation is insufficiently expressed with just one parameter-position information. Yet, little else is provided by the FLOLS. It would be difficult for the pilot to control all parameters at once if he were given information on all parameters separately. It becomes a manageable task to control all parameters if a pilot is given deviation information on all parameters in an integrated manner, i.e., information on his current flight path, projected into the future, as deviations from a required glideslope reference. With such information the pilot is informed of where he is going to be with respect to the glideslope for any given position and motion of the aircraft with respect to it and the aircraft's control inputs. This information will tell a pilot if he is off or on the glideslope; if off the glideslope whether moving toward or away; if on the glideslope whether staying on or moving off. This information is necessary because the control response is initially different in each of these cases (see Table I.)

Also very important while the aircraft is moving away or toward the glideslope (i.e., not steady) is the rate of motion away or toward. This rate information is necessary for smooth corrections without overshoots and to maintain and achieve a steady state after returning to the glideslope. It should be mentioned that the glideslope (however established) is moving with the carrier. Therefore the flight path described by an aircraft, if always steady on glideslope, would be an angle less than the glideslope angle set on the carrier. From the pilot's standpoint the motion of the glideslope represents a small constant forcing function to his "tracking task" when the Fresnel system (i.e., FLOLS) is used to establish the glideslope.

For lateral control the pilot needs aircraft roll and yaw status information as well as line-up information. Since, some pilots do not line-up

Table I

Appropriate Control Action for Each Combination of Conditions

	Glidepath Steady Relative to Glideslope	Aircraft Moving Away From Glideslope	Aircraft Moving Toward Glideslope
ON glideslope reference	Do nothing	Pitch nose up (or down as appropriate) until motion away is eliminated or predicted to be eliminated in the near future	NA
OFF glideslope reference	Pitch nose up (or down as appropriate) to start motion towards glideslope	Pitch nose up (or down as appropriate) to arrest motion away and to reverse it towards the glideslope	Pitch nose up (or down as appropriate) to increase or decrease motion towards glideslope; finally to damp out motion towards to achieve a steady state on the glideslope

All aircraft are assumed to be equipped with APC. The amount and duration of pitch up or down control input is a function of the magnitude of the motion rates to be nullified and/or the distance away from glideslope as perceived by the pilot.

until late in the approach; own heading and ship's heading or bearing information should be presented. Information requirements are summarized in Table II.

Information Not Included

Two other types of information considered for inclusion were pitch angle and predicted touchdown point. They were not included for the following reasons.

Pitch angle is already displayed in most aircraft. But it is not necessary to incorporate it separately into the predictor display during the approach because the pilot already controls it in terms of angle-of-attack.

Predicted touchdown point is a prediction of where (on the basis of the flight path of the aircraft, its rates and acceleration, pilot's control inputs, aircraft predictor model, predicted ship position, and predicted ship motion) the aircraft would touch-down in relation to where it should touch-down. There are some difficulties with this synthesized piece of information.

1. The carrier landing control problem is more than just hitting the right touch-down area in the ocean as was discussed earlier. It is that plus the additional requirement of staying within certain terminal parameters. Of course, terminal aircraft parameters cannot be predicted because pilot's control inputs cannot be predicted.

2. A complication arises in the lateral part of the prediction. Some pilots parallel a carrier course until near the final approach phase. Line-up is difficult until this later phase, which means that predicted touchdown would always be off laterally until then.

3. Predicted touch-down points based on carrier motion could lead to deck chasing control activity by the pilot as a way of adjusting terminal parameters to ship motion. There is some question whether this is desirable practice or not and if so when it should be practiced. This should be unnecessary, however, if control accuracy is increased sufficiently to permit pilots to stay close to the optimum glideslope.

Table II.

Carrier Landing Information Requirements

Information Required in Final Approach	Currently Available		Can be Supplied by Carrier Landing Predictor Display
	Day	Night	
1. Glideslope reference (current required position)	Meatball of FLOLS - No heave stabilization. Sensitivity of information changes with range. Inaccurate until about 3/4 miles out, or 15 seconds to touch-down	Same as day	Symbolic representation of glideslope reference extending from now to future.
2. Future glideslope reference (future required position)	Currently unavailable	Currently unavailable	Symbolic representation of glideslope reference extending from now to future.
3. Aircraft's flight path (current position relative to reference)	Relative displacement of meatball with respect to datam bar. LSO advice. (NOTE: LSO and FLOLS are not on same reference)	Same as day	Symbolic representation of glideslope reference relative to predicted aircraft's flight path.
4. Aircraft's future flight path	Inferred from external visual cues and own aircraft daynamics. Inferred trend advice from LSO and SPN-10	Currently unavailable	Symbolic representation of glideslope reference relative to predicted aircraft's flight path extending into the future according to control inputs.
5. Current relative motion rate between flight path and glideslope	Inferred from visual cues and own aircraft dynamics. Inferred trend advice from LSO and SPN-10.	Currently unavailable	Glideslope reference and aircraft flight path symbols will change perspective constantly as a function of aircraft positions and rates.

Table II (Continued)

Information Required in Final Approach	Currently Available		Can be Supplied by Carrier Landing Predictor Display
	Day	Night	
6. Future relative motion rate between flight path and glideslope	Currently unavailable	Currently unavailable	Glideslope reference and aircraft glidepath symbols will change perspective constantly as a function of lags and accelerations.
7. Lineup information	Carrier deck with centerline	Runway lights and drop lights	Lateral glideslope information can be integrated with vertical glideslope information to minimize pilot's scan.
8. Angle-of-attack	Angle-of-attack index display in canopy	Same as day	Angle-of-attack status can be integrated into display to minimize pilot's scan.
9. Aircraft heading	Follow ships wake or use cockpit instruments (e.g., TACAN or compass)	Cockpit instruments or reference lights on ship	Heading information can be integrated into display to minimize pilot's scan.
10. CVA ready deck	Radio information or FLOLS	Same as day	Warning symbol can be integrated into display.
11. Roll angle and yaw angle	Qualitatively available outside cockpit. Quantatively available inside cockpit	Same as day (when ship is visible)	Quantitative and qualitative roll and yaw information can be integrated into display to minimize pilot's scan and to maintain motion orientation compatibility.

4. A necessary ingredient in predicting touch-down point is predicting ship motion. This is currently beyond the state of the art for predictions more than six seconds with any accuracy. However should ship motion prediction become perfected, such data could be used in a better way perhaps than for predicting aircraft touch-down point. This would be to predict the location of the intended touchdown point. Since the glideslope starts from this point, glideslope position could be corrected with ship motion predictions. This does not mean that the glideslope would move with the ship because the glideslope would be stabilized for the predicted intended touch-down position at touch-down time. The only glideslope movements which would be discernable are occasional slight drifting movements resulting from improvements in the prediction of the intended touch-down position as a result of closing range.

Predicted touchdown information might be usefully introduced later in the approach when predictions would be more valid; but not to elicit late corrections and consequent deviations from terminal landing parameters. Predicted touchdown information may be more useful as a criterion for wave-off or attempted arrestment to be used by the pilot, LSO, or both.

PROBLEMS AND DEFICIENCIES WITH INFORMATION CURRENTLY AVAILABLE

At night some glideslope information (vertical component) is currently made available to the pilot with the Fresnel Lens Optical Landing System (FLOLS) and from LSO advice. The "meatball" tells the pilot his position with respect to the glideslope. Most of the time information is not sufficiently accurate, i.e., the pilot only sees the center ball, one ball high or low, or two balls high or low. What makes matters worse is that in each position the ball can mean a different distance from the glideslope at different ranges from the carrier, i.e., the quantitative sensitivity of each ball changes as a function of range. If this is not enough, the FLOLS is physically located on the carrier which is moving forward, pitching, rolling, yawing and heaving. The FLOLS is pitch and roll stabilized (with some time lag) but the "meatballs" are still in motion especially closer in. What the pilot gets is unstable and gross quantitative position information (from glideslope) which changes in meaning as a function of range. The furthest range at which this information is useful is about 3/4 miles from the ramp which typically gives the pilot about 30 seconds from touchdown to achieve his control objectives. He therefore has little time to do the job properly even if the information available were accurate or adequate. Information requirements not currently met are summarized in Table II.

By examining Table II., we can see the major differences in information currently available in the daytime and at night. These are aircraft's future glidepath position relative to the glideslope reference and the current change rates of that position. It is true that the pilot currently gets meatball movement information but ball motion rates are confounded with aircraft motion rates and changing glideslope reference position requirements. Therefore aircraft's position and change rates of position relative to the glideslope are not provided by the meatball. Both types of information are unavailable with the FLOLS and are synthesized by the pilot using daytime visual cues and his learned internal model of aircraft dynamics. Since the visual cues are missing at night so are these vital pieces of information. This may account for the higher night accident rates.

In addition we see that during, day and night, two other pieces of information are missing: future required position on the glideslope and future rate information. The first refers to the fact that the pilot doesn't have a visible position on the glideslope to fly to, he only knows at each point in time, where he is with respect to where he should have been. Since control actions only affect future positions and he has no required position reference for those future positions, he has no updated control reference. He is always guessing from past control references. A glideslope reference coded perspectively so that a 3D glideslope along its full range can be seen in the display would eliminate this deficiency. The second missing piece of information has to do with control time lags and accelerations which determine the aircraft's motion rates in the future. This type of information is necessary for smooth, quick and accurate control.

In summary, the table identifies a minimum of 11 information items which a pilot should have during the approach, nine of which should be available constantly. Of those nine, two are currently missing in the daytime and four are missing at night. Of the information items available, four of the seven daytime and three of the five nighttime items are poor in quality or must be inferred by the pilot from indirect information.

INFORMATION IMPROVEMENTS

A significant improvement could be realized in carrier landing by simply providing the same information which the FLOLS attempts to provide externally, in a cockpit display so that FLOLS deficiences can be eliminated. The SPN-42 already provides glideslope reference and aircraft position deviation information to the ACLS. Further, a data link is available to pass information to the cockpit. If "meatball" information instead of command flight direction information were trans-

mitted and displayed to the pilot,then the meatball information would be available at much greater ranges than it currently is thereby giving the pilot much more time to get on and stay on the glideslope. In addition, the sensitivity of the information would be constant, accurate and independent of ship motions. That alone should lead to improvements day and night. Furthermore, if the required information already discussed, which is currently missing, were to be added in a proper manner, such as is possible with the predictor display currently being studied, and if all the "poor" information items were improved, carrier landing performance should be greatly improved day and night with night performance similar to day performance.

Preliminary Display Input Requirements

From ship	ship's heading and speed
From SPN-42	altitude error (from reference glideslope) lateral error (from reference glideslope) approach path angle stabilized altitudes range sink rate closing speed
From aircraft	stick commands angle-of-attack roll angle yaw angle heading APC throttle commands percent RPM power requirements accelerometer outputs

PREDICTOR DISPLAY DEVELOPMENTS

A predictor instrument display graphically displays to the operator of a system, through appropriate symbology and dynamics, a prediction of future outputs. A predictor display must always be configured to suit a particular system or vehicle, or simulation of a system or vehicle, operating in real time. Predictive information displayed is generated by a time accelerated model of the system or vehicle to be mechanized.

The fast time model operates by sampling present values in the real time model and computes the extrapolated future values that the real time system will eventually acquire. It does so at a highly accelerated computation rate, and reiterates the fast time computation with new initial conditions as the real time model values change. The time acceleration factor of the fast time model is usually several orders of magnitude greater than the time base of the real time system, and the computations are reiterated many times each second. The output of the fast time, repetitive operation model is coupled with display symbology signals to display the present and future output of the system on a CRT or other display.

Three major and distinct end products were produced in achieving a "breadboard" predictor display in Phase A. The real time F4-B model in a landing configuration, a fast time predictive model of that F4-B simulation, and the display symbology used in presenting the predictor information were generated.

Also during Phase A, two complete iterations of those end products were produced. A simplified F4-B in real time, a corresponding fast time predictive model and a number of display symbologies were first assembled and tested in the Dunlap and Associates, Inc. laboratory. Later in Phase A a more sophisticated fast time predictor model was mechanized to operate in conjunction with the existing F4-B real time model in the Pt. Mugu Test Center research laboratory. Also, some different display symbols were explored and displayed.

PREDICTOR DEVELOPMENTS AT THE DUNLAP LABORATORY

Real Time Model

A simplified real time model of an F4-B aircraft in a landing configuration and trimmed for a 3.5° glideslope was mechanized in the D & A laboratory to provide a vehicle upon which development of an aircraft landing predictor could be based. The model was derived from

the F4-B simulation used by the Pt. Mugu Naval Test Center in their development of the contact analog simulation (17). In the D & A laboratory only range (x) and altitude (z) parameters were utilized; lateral motions being ignored. Considering the equipment limitations and the purpose it was to serve, the model was kept as simple as it reasonably could be while adequately representing the major flight dynamics of the aircraft. The derivation of the model and resulting analog diagram appear in section 1 of the appendix. The model included APC control and the only pilot inputs were vertical control stick signals.

Fast Time Predictor Model

The fast time repetitive predictor model was structured on a replica of the simplified real time model. The analog diagrams for it are presented in Section 1 of the Appendix. The fast time model was time accelerated x1000 yielding a predictor span of about 12 seconds. The model was cycled and updated at approximately 41 Hz. Experience with the 12 sec. prediction span led to the conclusion that a longer span would be desirable. Increasing the span became an objective for the second mechanization at Pt. Mugu where a 30 second time span was selected. The only differences between the fast time and real time systems for this mechanization were the addition of fast time, repetitively operating, control switches to the several integrators of the model, provision for summing initial condition values into the fast time circuitry and time acceleration gain changes to the integrators.

Side Looking Predictor Display

The predicted x-z output was mechanized first in the D & A laboratory as a side-looking predictor display and various presentation and scaling factors were explored. While the side view predictor display is a necessary and useful tool in the mechanization and calibration of a predictor model, there is some difficulty in scaling it as an effective display for the actual carrier landing task. Approach range consists of approximately 10,000 feet covered by the F4 in approximately 1 minute. A 20 second predictor trace represents about 3300 feet down range. Aircraft altitude at a range 10,000' behind the carrier is approximately 610' decreasing to zero at touchdown (the carrier's flight deck is assumed to be at sea level). Thus, the range/altitude ratio is 10,000' to 610'. Range and altitude could be scaled one-to-one and displayed in the proper ratio, but if range were covered in the full width of the seven inch wide display, which is available, total altitude would be displayed in .42 inches. That would give a glideslope presentation with the appropriate slope but insufficient altitude accuracy would make the display totally useless for vertical control. A larger display would provide additional but still insufficient

accuracy. Also larger displays are impractical for installation in fighter aircraft. It is considered desirable to generate a landing display with a vertical or altitude sensitivity that allows the pilot to discriminate present or future predicted altitude with an accuracy of 1 foot otherwise aircraft control accuracy will be limited by the display. Further, it is desirable to cover an altitude range of about ± 40 feet from ideal glideslope altitude to insure that errors of that magnitude do not result in loss of a glideslope reference in the display. Attempts to get back on glideslope blind can easily lead to erratic and unsuccessful control in the approach.

Front View Predictor Display

Front looking, inside-out predictor symbology was developed next along with the necessary glideslope reference symbology discussed in the information requirements study section of this report. The relative motions of the two were analyzed to evolve a format for the display (see Figure 3.) The predictor trace has its origin at the display surface which is transformed to correspond to the center of moments of the air frame. The predicted trajectory is illustrated in the form of a perspectively diminishing flat path. The smallest width position or tip represents the most future predicted position. The curvature between the "near" end and "far" ends of the path describes the trajectory the aircraft will follow in the future. The predicted aircraft trajectory was corrected for a 3.5^{o} glideslope angle so that the desired ideal glideslope trajectory was normal to the display surface. Thus, when the pilot is flying directly "on glideslope" and has a path predicting that he will stay on glideslope, the predictor symbol appears as a straight line across the display. If the pilot starts to climb above the 3.5^{o} glideslope, the far end of the predictor trace will rise above the near end. Similarly, if sink-speed is increased above that necessary to maintain a 3.5^{o} down slope trajectory, the far end of the predictor will drop below the near end reference. See figure 3 for illustrations of those effects.

Both eliptically shaped spiral and rectangularly shaped tunnels were considered for the glideslope. Because of equipment limitations in the Dunlap and Associates laboratory, the symbology used was a perspectively coded tunnel painted on the CRT display in the form of an eliptically shaped spiral. It was large at the near end and became progressively smaller as the pilot looked forward into the future. The near end of the glideslope tunnel was moved up or down as a function of present algigude error from glideslope. It was determined that the far end of the glideslope which is tied to the carrier's position could be given proper movement through an appropriately scaled combination of aircraft pitch angle (from the trimmed angle) and glideslope altitude error. Such a mechanization approach is applicable to the vertical prediction only, and would be modified as required for the full vertical and lateral dynamic system required for Phase B.

PT. MUGU PREDICTOR DEVELOPMENTS

Real and Fast Time Models

For a demonstration and briefing, the real time F4-B simulation as used in previous Pt. Mugu studies was re-activated. A more accurate vertical, only, fast time predictor model was derived which had more complex dynamics than were obtained in the D & A laboratory model. The derivations and analog circuit diagram of the more sophisticated predictor model appear in Section 2 of the Appendix.

To permit mechanization of the fast time predictor model and glide-slope symbology at Pt. Mugu, development of FET transistor gating switches was necessary. They were used to cycle the fast time model. It was also necessary to use novel analog techniques of division to process the fast time predictor signals. Numerous other changes in the existing hardware at the Pt. Mugu facility were necessary to accomodate the predictor model, make available the necessary input signals, and to generate the predictor symbology on the cockpit display.

The fast time model received its necessary initial condition signals and other real time model inputs from both the F4-B computer model and the Contact Analog Display Generator (CADG) (18, 19). That signal routing was necessary to enable the predictor model to be interfaced properly with the existing simulations.

Various alternative values and settings and other problems related to display scale, perspective coding, symbol generation, display dynamics and predictor model parameters were worked out and completely or partially resolved in detail for the display that was mechanized for the briefing at the end of Phase A.

Some mechanization problems remain to be resolved during Phase B and some parameters require further testing to determine final recommended values.

Side-Looking Predictor Display

During Phase A activity at Pt. Mugu, a side-looking predictor display was used only as a check-out and calibration tool, and the display described in the next section was not fully mechanized.

Front View Predictor Display

The front view predictor display was fully mechanized with the same dynamics described previously for the Dunlap and Associates laboratory

version. The aircraft flight path was presented as a flat path painted on the display in the form of a decreasing width square wave. The pathway presented a prediction span of 30 seconds into the future.

The glideslope reference used was a rectangular tunnel generated as a series of concentric rectangles. The glideslope is coded perspectively being largest at the nearest point and smallest at the farthest point. The far end of the glideslope is linked with the aircraft carrier. The dynamic motions of this glideslope were the same as the D & A laboratory version described previously. Additional front view display features are described in the display description section. The glideslope reference was generated as part of the fast time model simulation and was validated by on-line continuous comparison with the same reference as generated in Pt. Mugu's Contact Analog Display Generator (18, 19).

The front view display mounted in the cockpit is a raster scan type, while the predictor flight path and glideslope reference symbols are written directly via analog signals. To convert analog to raster, the analog display was generated on a CRT oscilloscope, picked up by a TV camera and then transmitted via cable to the cockpit display.

GENERAL PLAN FOR PHASES B AND C

DESCRIPTION OF DISPLAYS TO BE DEVELOPED

The displays to be developed and evaluated in Phase B are described in this section.

Baseline Or Conventional Information Display

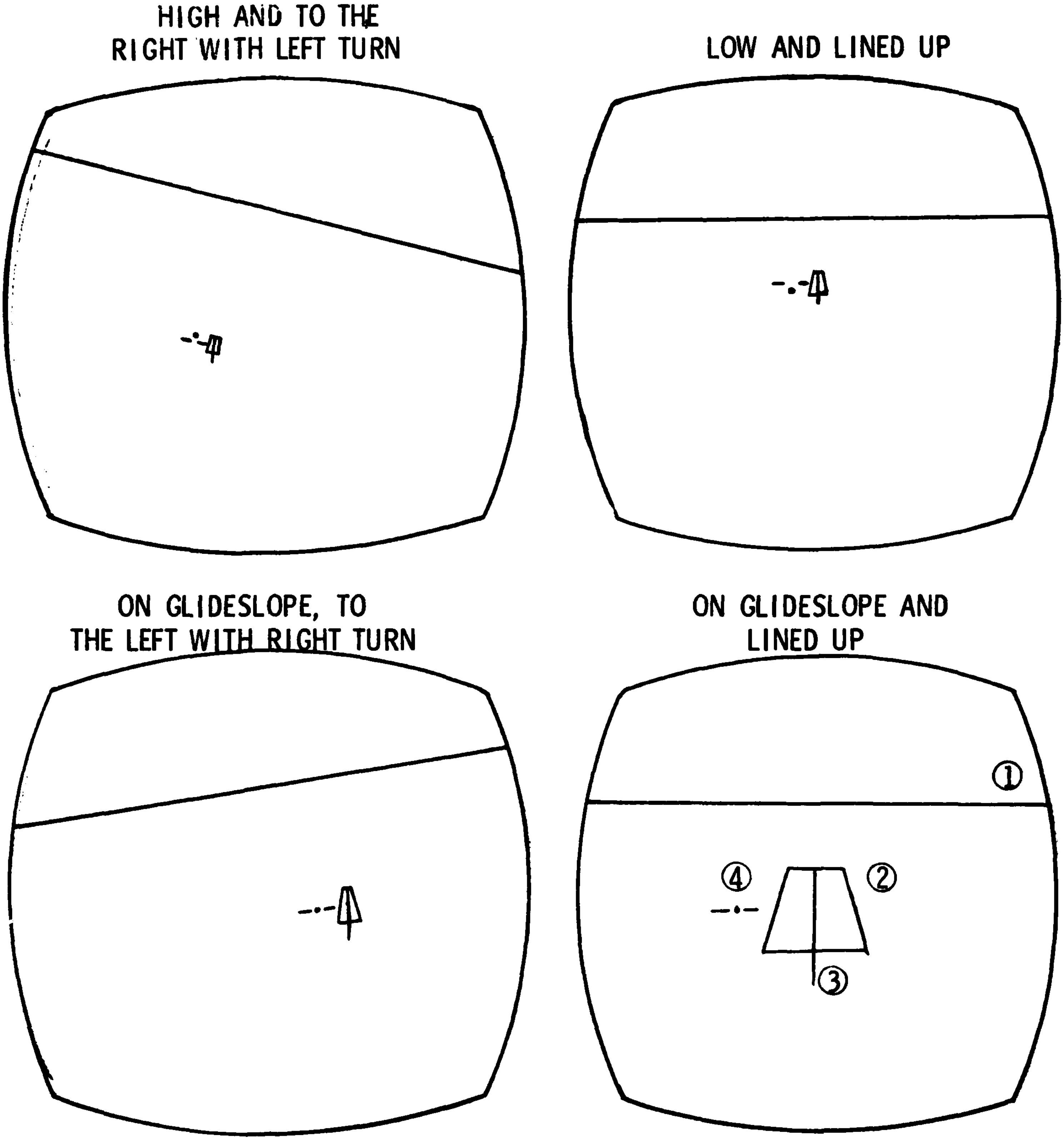
Performance obtained with a "baseline" display will be used as the basis for evaluating the effects of predictor displays on carrier landing performance. If possible the display will represent "real world" information similar to that currently available to jet pilots through the front canopy during night landings. We hope that the display will be inside-out in orientation and the essential information elements will be; (1) moving horizon line, (2) carrier runway lights, (3) droplights, and (4) the meatball and datum bar. A desirable baseline display is illustrated in Figure 1. In general, the display will have the same "real world" motions as the Vertical Contact Analog Display (VCAD) developed at Pt. Mugu (18, 19). Other information elements are: angle of attack indexer (to be located to the left of the display), control stick feedback, and other cockpit instruments to be determined furing Phase B.

Additional baseline display details are:

a. Horizon line (dim grey)
   - moves with aircraft roll
   - moves with vertical changes in aircraft aim point

b. Carrier landing lights and "drop" lights
   - lines represent parallel lights rather than tunnel lights
   - pattern of lights change in size and perspective as a function of range
   - angle between droplights and carrier changes as a function of aircraft offset from glideslope centerline
   - entire pattern moves left and right with aircraft heading and lateral errors
   - entire pattern moves up and down with aircraft aim point and altitude errors

c. Meatball and datum bar
   - will have five discrete ball positions
   - stays tied to appropriate spot to left of carrier landing lights



1. Horizon
2. Pattern formed by carrier landing lights
3. Line formed by row of droplights
4. Meatball and datum bar

Figure 1. Proposed baseline display

- use minimum reasonable size and keep size constant (unless it should be easier to change size) with range
- displace ball vertically with respect to datum bar as a function of altitude error as it would be seen by a pilot at each range assuming a "line" stabilized glideslope. No heave movement of meatball will be attempted.
- at 1 - 1/4 miles introduce datum bar only
- at 3/4 add meatball in proper position

d. Stop display motion at touchdown

e. Display scaled the same as in VCAD

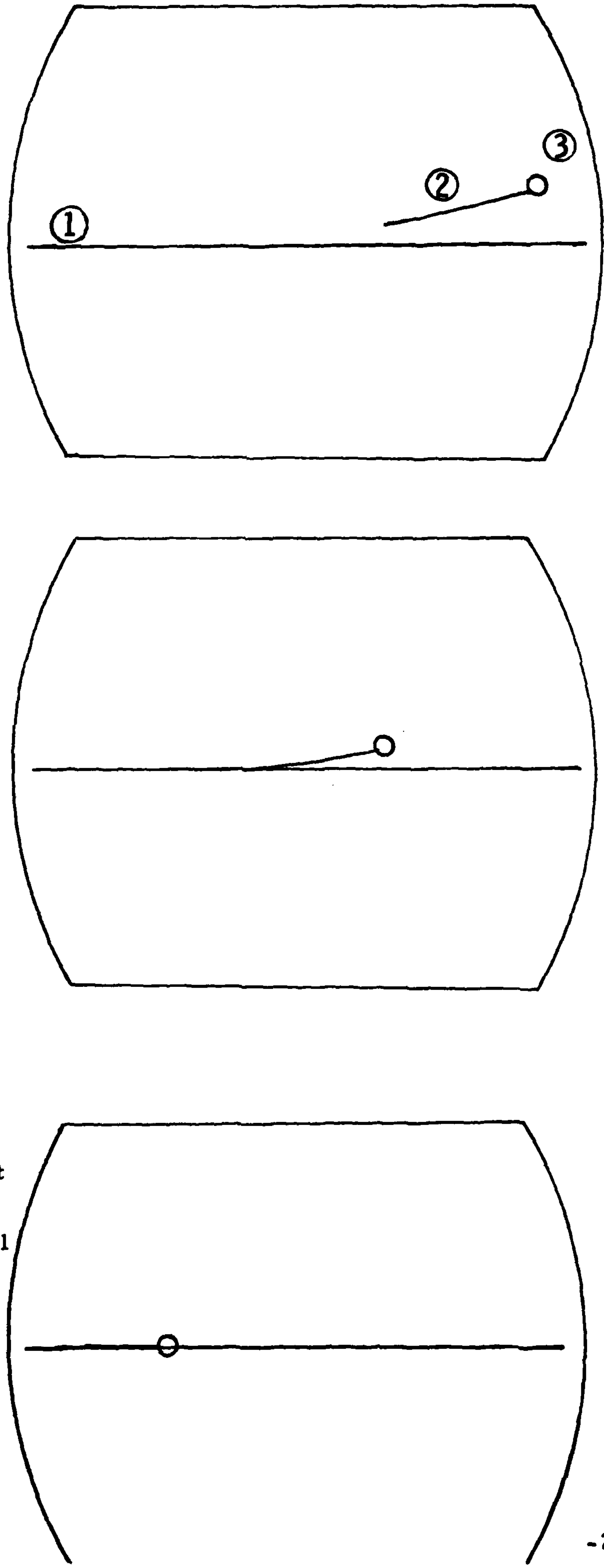
Side View Predictor Display

The side view display has an inherent outside-in orientation. Also, it provides only range (x) and altitude (z) information. No lateral (y) error information is provided. For this reason, the total simulated landing control task will require that the side view display be used with the baseline display. That will be analogous to having both a side view display in the aircraft cockpit and the front view through the canopy.

The side view incorporates the two major information constructs discussed in the display requirements Section viz., (1) the glideslope and (2) the predicted flight path. It also has an aircraft symbol (3) represented by a dot or small circle. The display will appear similar to Figure 2. The vertical dimension represents altitude and will be scaled to about 1" = 12' - 16'. The horizontal dimension represents range and is scaled to represent a distance of about 10,000'.

The horizontal line represents the glideslope. The glideslope has not been given a descending slope so as not to mislead the pilot in his control judgement. A realistically angled glideslope would provide a strong impression of a Euclidian-like control space. Because of the required large scale differences between the vertical and horizontal, aircraft motions would be distorted and any reasonable glideslope angle would be arbitrary and incorrect.

The predicted flight path is represented by the line attached to the aircraft symbol. The aircraft moves from right to left in the display to make it compatible in orientation to the view seen by a pilot flying a real aircraft as he makes his left turns on the port side of the carrier looking towards the glideslope. It is also compatible with the view available to the LSO as he watches an aircraft approaching from the port side of the flight deck. The predicted path curls up or down to represent an



1. Glideslope
2. Predicted flight path
3. Aircraft symbol

Figure 2. Proposed side predictor display

upward or downward prediction. When the aircraft nears the carrier and the predicted flight path has reached the end of the glideslope, the predicted path on the display will proceed to shorten as the aircraft continues to touchdown.

Summarized, the side view display characteristics are as follows:

a. Horizontal fixed line

b. Vertical is scaled 1" = 12' - 16'

c. Horizontal is scaled to full glideslope range

d. Dot (•) represents the aircraft
   - aircraft and predictor move from right to left with closing speed
   - aircraft and predictor move vertically with altitude error and sink speed

e. Predictor flight path dynamics are generated with respect to glideslope, (e.g., a straight and level flight path position represents a trajectory parallel with the glideslope, not straight and level flight with respect to the earth).

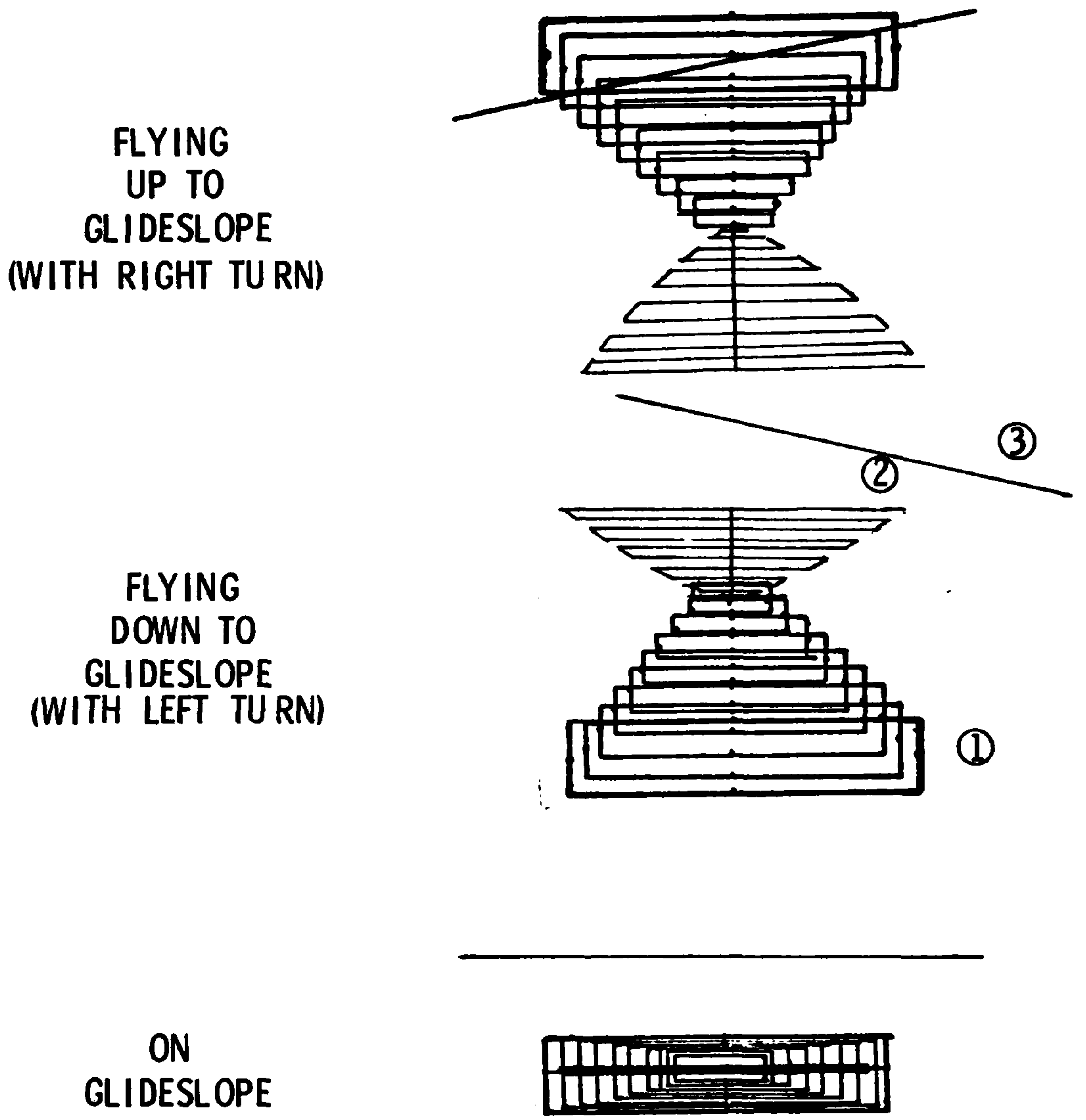
Front View (Vertical Only) Predictor Display

The front view display should have the same inside-out orientation as the baseline display or the pilot's view through his front canopy. It should provide current glideslope error information for both altitude (z) and line-up (y) but provide predicted information only for vertical or altitude control. In addition, range (x) would be coded perspectively through symbol shape, size, location, and motion.

The front view predictor display illustrated in Figure 3 contains three basic information elements: (1) a glideslope, (2) predicted flight path and (3) a horizon line.

The glideslope is represented by a rectangular tunnel scaled to be about 20' high and 40' wide. The far end of the glideslope symbol is fixed to the carrier position. The near end moves up or down as a function of altitude error changing the perspective shape of the entire glideslope as it moves.

The predicted flight path is represented by a flat "roadway-shaped" symbol eminating from the aircraft structure (i.e., the near end always



1. Glideslope 2. Predicted flight path 3. Horizon Line

Figure 3. Front view (vertical only) predictor display

fixed near the center of the display.) The shape of the flight path symbol and the position of the far end is under pilot control through his control stick. To achieve zero glideslope altitude error the near end or sides of the flight path must be lined up with the vertical middle of the glideslope (indicated with brightened spots or dots).

The flight path in the vertical, only, front view predictor display does not provide predicted lateral or roll aircraft motions. (However, heading and roll information as well as other motions similar to the VCAD are provided by the motions of the horizon line.) Furthermore, while the near end of the glideslope displaces vertically with respect to the far end to provide vertical motions in perspective, it does not displace laterally with respect to the far end to provide lateral motion. Lateral information is provided only by a lateral offset of the entire glideslope (i.e., the near and far ends are locked laterally with respect to each other). The far end, being tied to the carrier, will move left or right as a function of aircraft heading error. To facilitate line-up, both the glideslope and flightpath symbols will have brightened dots or lines in the lateral middle so that any misalignment will become immediately obvious. A summary of these and additional display information characteristics follows:

a. Horizon line
   - moves as in baseline display and in VCAD

b. Glideslope
   - rectangular tunnel with lines or brightened dots on sides to indicate vertical center of glideslope and on top and bottom to indicate lateral center
   - since the far end is tied to the carrier's position, it moves up and down and left and right as does the carrier symbol in the baseline display
   - near end moves up and down with perspective changes as a function of altitude error only
   - scaling provides total height of glideslope to be about 20'
   - total width of glideslope is about 40'
   - does not roll with horizon but remains in same fixed roll orientation of the flight path
   - boxes are blanked out one at a time starting from the end as aircraft approaches touchdown
   - brightness of all sides at the same range are even
   - brightness of boxes decreases towards the far end
   - sides of boxes appear to move towards aircraft to provide illusion of forward motion

c. Predicted flight path
   - perspective roadway - ladder type with line or brightened dots in the center of road

- prediction span is about 30 seconds
- brightness of road decreases as you go into the future

Front View (Full Motion) Predictor Display

This display would be essentially the same as the predictor display described previously except that lateral and roll predictions and glide-slope perspective motions will be added if possible. The motions in this display would provide an impression to pilot subjects that a three dimensional glideslope emanates from the carrier and that the aircraft could be flown anywhere in space around the glideslope with all the proper attending perspective views of the glideslope as seen from the canopy. Figure 4 illustrates approximately how the display might appear. Furthermore, the predicted flight path which in this display provides vertical, lateral and roll predictions up to 30 seconds into the future, becomes a roadway which the pilot can place anywhere he desires within the limitations of the response characteristics of his aircraft. The far end of the glideslope is fixed to the carrier and moves as a function of aircraft motions as they do in the VCAD or in the baseline display. The near end moves in any direction, appropriately changing the perspective of the glideslope as a function of changes in the aircraft's vertical and lateral position from the glideslope, including offset motions due to aircraft heading errors. The horizon line moves as in the VCAD and in all of the other front view displays. The glideslope rolls with the horizon line in this display. The predicted flight path is changed in shape as a function of all control stick inputs as they are transformed by the fast time F4 model. A summary of the information elements and characteristics for the full motion front view predictor display follows:

a. Horizon line
   - moves as in baseline display and in VCAD

b. Glideslope
   - same as in Vertical Only Predictor Display except:
   - lateral perspective changes accompany lateral offset of far end as a function of lateral error
   - offset of glideslope occurs also as a function of heading changes
   - glideslope rolls with horizon line

(In short the glideslope changes perspectively as a 3D object in space with VCAD motions.)

c. Predicted flight path
   - same as in Vertical Only Predictor Display except:
   - predicts roll and lateral movements as well as altitude

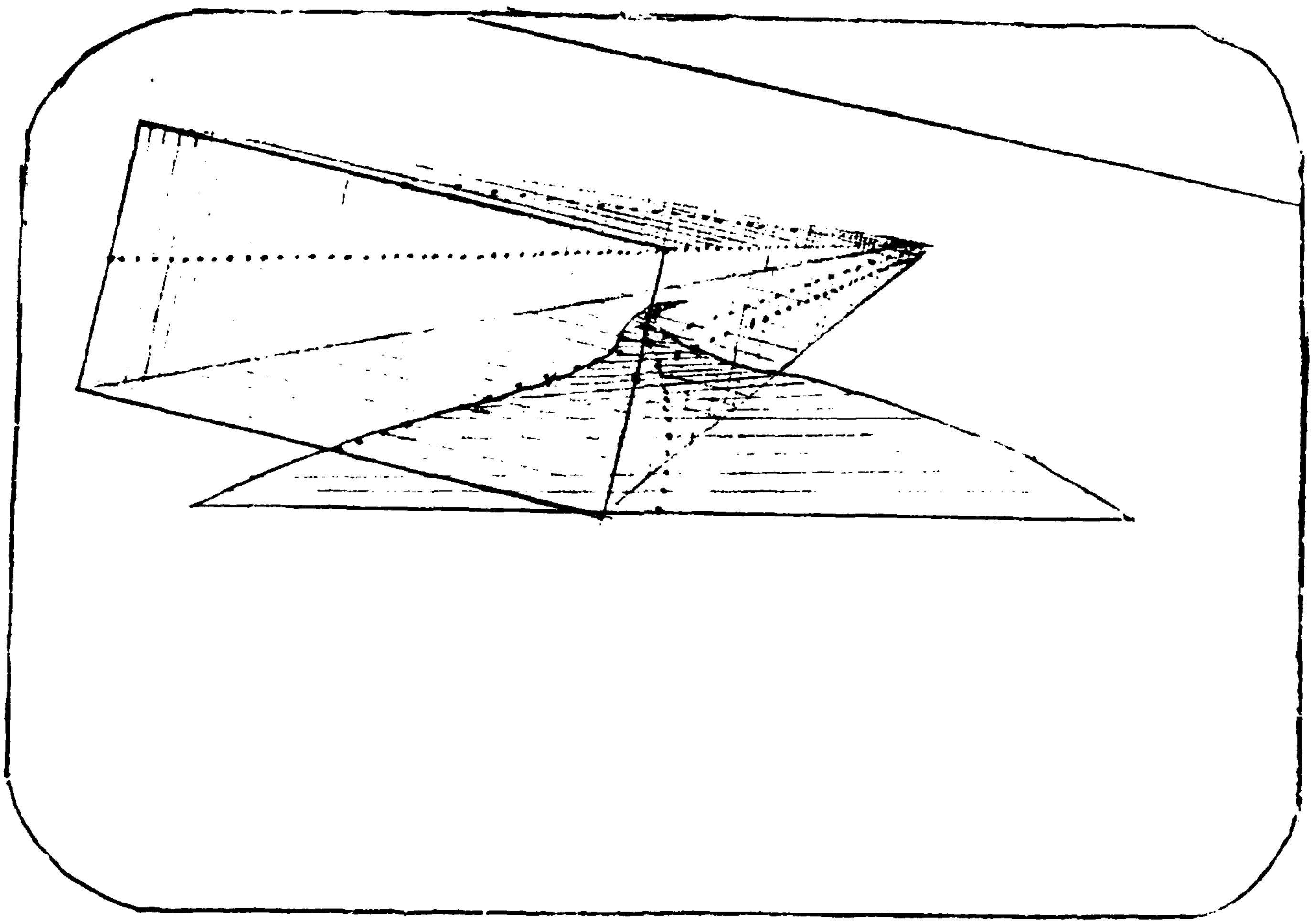


Figure 4. Front view (full motion) predictor display

- flight path changes shape (perspectively) in roll, lateral movement and vertical movements

Other Experimental Requirements

- Angle of attack indexer located to left of every display or in the case of the side view predictor display to left of baseline display. Angle of attack indexer is used in all display configurations. Angle of attack information is taken from APC values in the F4 real time model.

- Capability to switch quickly from one configuration to the other (i. e., less than 5 minutes including any adjustments).

- Capability to control runs from outside the subject's cockpit. Remove that capability in present cockpit configuration.

- Two glideslopes are needed.
  1. One will be essentially the same as that used in the VCAD. This one will be used for all displays except the meatball display.
  2. The other will be a meatball - based glideslope. This glideslope will be similar to a line-stabilized glideslope. The meatball will have 5 discrete positions.

- All glideslope errors will be measured with glideslope 1.

- Other displays to be used in the fixed base cockpit will be determined later.

PHASE B EVALUATION

The primary objective of Phases B and C is to prepare for and run a simulation experiment with pilot subjects to determine the effects of experimental predictor displays on carrier landing performance. The principal tasks for Phase B are to: complete the development of the displays, prepare the simulation setup for the experiment, and run informal trials. Phase C tasks include conduct of the full experiment, and analysis and documentation of the results.

Phase B Informal Trials

Toward the end of Phase B, informal trials or subject runs will be conducted with the various displays developed. The purposes of those trials

will be critically important to the remainder of the carrier landing predictor display program and their outcome will shape the conduct of Phase C.

The purposes of the informal trials are to:

- Evaluate the baseline display.

  Evaluate and insure that the baseline conventional-information display provides a reasonable presentation of the essential information now available to pilots in the real world during night carrier landings and that it is presented in a realistic manner.

- Determine the reliability of the measurement system and sensitivity of the selected measures.

  One of the major concerns of this project is whether or not the task difficulty to be experienced by our subjects using realistic landing situations is at a level which permits performance differences between displays to show up using straight (i.e., non-adaptive) performance measures. These measures are easier to use, provide a more comprehensive evaluation of the displays, and permit many more interesting data comparisons than is possible with adaptive measures. If performance differences between displays are small (which is not expected) then an adaptive measuring system with appropriate forcing functions (e.g., cross wind and/or burble) will be set up to ensure significant performance differences. That necessity would have a major impact on the experimental design of Phase C.

- Make a preliminary evaluation and selection of predictor displays.

  It is not expected that all three predictor displays can or should be part of the full Phase C experiment. The number of total simulation runs and subjects necessary for a proper counterbalanced experiment and for thoroughly training large numbers of subjects on that many displays is prohibitively expensive and time consuming. The purpose of developing more than one display during Phase B is to insure that selection of the better of opposing predictor display approaches will be made on empirical grounds in addition to, rather than exclusively for, analytical reasons. Dunlap believes that the selection can be made during the informal trials without a complete experiment with full experimental controls. If there are no large differences in performance between the three displays then one of the front views can be safely dropped. If one display is much worse than the other two then it will be dropped. If the remaining two are front view displays one of them can also

be dropped safely. If one display is much better than the others, then the other two will be dropped. In any event, at least one front view display will be included for the Phase C experimental plan. The Phase C experiment will, therefore, be for evaluation of only one predictor display and two at the most against the baseline display.

- Determine the amount of training required for subjects on the selected displays.

  Before an evaluation, however informal, can be made of any of the predictor displays the subjects must have an opportunity to learn the displays thoroughly so that performance differencies arising from differences in familiarity with displays can be eliminated from the results. The number of landing runs necessary to achieve an asymptote on the learning curve or to meet a performance criterion during informal trials will provide valuable subject scheduling and experimental design information for final planning of the Phase C experiment. If the number of trials that are required for subjects to reach an asymptote is excessive and if subjects can meet a reasonable performance criterion with fewer trials than is required for reaching asymptote then the performance criterion will be used during Phase C.

TENTATIVE EXPERIMENTAL PLAN FOR PHASE C

The experimental plan presented here for Phase C is tentative. Phase B results will have a major impact on the final experimental plan. The tentative plan provides for the evaluation of one predictor display against the baseline display i.e., two display treatments. Should the evaluation of two predictor displays be indicated by Phase B informal trials then the same general plan will be repeated in its entirety for the other predictor display. It is believed that two such two-treatment experiments take less trials and resources than a single more complicated experiment involving three treatments because of the excessive counterbalancing requirements involved in a three treatment experiment.

Either or both of two broad questions that might be asked in the evaluation of predictor displays: (1) Which display can be learned the quickest? (2) Which display leads to better carrier landing performance? The experiment might accordingly consist of either or both sections, i.e., a learning section and/or a performance section.

Learning Section

Ruling-out Learning Order Effects

Frequently in experimental designs a counterbalanced trial-by-trial order in the presentation of treatments (or displays in this case) is used to

rule out learning effects. The procedure is typically employed during learning trials as well as during data gathering trials. But in those experimental designs the rate of learning itself is not a dependent variable as it is in this program. A counterbalanced trial-by-trial order in the presentation of displays cannot be used during learning trials because to do so would contaminate the learning curves. Therefore, our subject might start with one of the displays and work with it exclusively until they reach asymptote or until an appropriate performance criterion is reached. Then they will take up the other display. Of course, positive or negative transfer of training can also result from display learning order. Learning experience with the first display could confound the learning curves on the second display. To counterbalance those effects, half of each subject group will learn the baseline display first and the other half will learn the predictor display first. While individual subjects cannot be counterbalanced through trial order manipulation, subject groups can be counterbalanced through display learning order (see Table 3).

Ruling-out Pilot Bias

Operators who are well trained and who have had success with a particular display sometimes are reluctant to accept a new display. That can happen not because they are against possible better ways of doing things, or because of conservatism, but because of an unconscious reliance on the familiar, difficulty in making changes in mental set, or inability to reduce commitment to their current style of control sufficiently to permit their forming new control patterns which might be necessary for efficient control of the new display.

Carrier qualified pilots are already partially experienced with the baseline display by virtue of the fact that the information elements present during actual landings are similar to those present in the baseline display. Some of the pilots may, therefore, have a positive bias toward the baseline display or a negative bias toward the predictor which could contaminate the experimental results.

In spite of those possible biases it appears desirable at present to include carrier qualified pilots in the study. The Navy should be able to generalize from the experimental results to the population of fleet carrier pilots who daily experience the carrier landing problem. Also, it is that population which would eventually have to use the predictor display. To control bias effects, two subject groups are planned tentatively: qualified carrier pilots and unqualified pilots(see Table 3). Unqualified pilots should have less of a bias, if any, towards the baseline display but at the same time are not completely naive to flying or landing an airplane. Use

Table III.

Example of Possible Phase C Subject Groups and Treatments Design

		Learning Section (Subject running order will be randomized)			Performance Section (Subject running order will be randomized)
		Subject	Learn Baseline	Learn Predictor	
Carrier Qualified Pilots	Learn Baseline First	1.	x trials	y trials	Subjects receive 40-60 trials in BPPB display presentation order (about 20-30 trials for each display)
		2.	x trials	y trials	
		3.	x trials	y trials	
	Learn Predictor First	4.	y trials	x trials	Subjects receive 40-60 trials in BPPB display presentation order (about 20-30 trials for each display)
		5.	y trials	x trials	
		6.	y trials	x trials	
	Learn Baseline First	7.	x trials	y trials	Subjects receive 40-60 trials in BPPB display presentation order (about 20-30 trials for each display)
		8.	x trials	y trials	
		9.	x trials	y trials	
Non-Carrier Qualified Pilots	Learn Predictor First	10.	y trials	x trials	Subjects receive 40-60 trials in BPPB display presentation order (about 20-30 trials for each display)
		11.	y trials	x trials	
		12.	y trials	x trials	

of non-pilots as subjects is tentatively rejected because of the inordinate amount of training which they might require before they could be brought to the same level as the qualified carrier pilots.

Experimental Questions in Learning Section

The experimental questions being asked in the learning section are:

1. Which display is learned quickest i. e., which display permits subjects to reach an asymptote or performance criterion in the fewest trials?

2. Which subject groups will learn quicker with the predictor display? The baseline display?

3. What effects will learning order have on learning speed of of all subjects with each display? Of different subject groups with each display?

Learning Data Treatment

Any of the measures discussed later in the performance measures section of this report could be recorded continuously during any learning trials.

Learning Curve Approach

If the learning curve approach is selected as a result of Phase B informal trials, then every five learning trials, for example, might be considered a "block" and means and variances could be computed for the 5 trials as a group. The means and variances could be used later as data points for plotting learning curves. The curves for each parameter for each subject group x learning order x display could be compared using trend analysis techniques.

Performance Criteria Approach

If the performance criterion approach were taken, actual performance scores would be evaluated. The aggregate scores for all landing parameters could be compared with a performance criteria to be selected later. A tentative joint criterion might be:

- clear the ramp with no less than 2'
- no more than 10' off centerline at touch down, left or right
- no more than 22 ft./sec. sink speed at touch down
- catch one of the wires (i. e., longitudinal error must fall within wires 1-4)

Performance Section

After subjects have learned both the baseline and predictor displays an appropriate number of performance runs (to be determined in Phase B) might be made for each display in a counterbalanced display order presentation (see Table 3). That design will systematically control day to day differences in subject performances by assuring that those effects apply to both displays. The schedule of subjects run in that manner would be according to a blind randomized scheme.

Any measures could be recorded automatically for any runs. Most of the same controls discussed in the learning section apply to the performance runs. Data could, therefore, be grouped according to the subject groups and learning order groups. During both learning and performance trials tracings can be made of approaches and terminal scores recorded so that knowledge of results could be made available to the subjects to increase motivation and facilitate learning.

Experimental Questions in Performance Section

The experimental questions to be asked in the performance section are:

1. Which display yields better performance i. e., lower landing error and glideslope error scores.

2. Which display yields more consistent performance i. e., lower variance in error scores?

Performance Measures

Carrier landing performance measures are of two types, terminal measures and approach measures. Measures taken will be selected from the following.

Approach measures include:

- altitude error at discrete ranges and ramp
- lateral error at discrete ranges and ramp
- mean square altitude error
- mean square lateral error
- sink speed at discrete ranges and ramp
- angle of attack errors

Terminal measures include:

- longitudinal error from wire 3
- lateral error from centerline
- sink speed at touchdown

Those measures can be converted to:

- bolters
- wire number
- ramp strikes
- hard landings

APPLICATION OF RESULTS

As stated at the beginning of this report, the purpose of this three-phase program is to develop a predictor display and determine its effect on pilot performance in landing on aircraft carriers. If the experimental results of Phase C indicate that the predictor display does improve carrier landing performance, then extensive descriptive data on the predictor display and how it operates will be included in the final report for Phase C. Some further study may be required in special areas before complete specifications for an aircraft prototype can be written. These areas may include: selection of type of display (e.g., HUD, electro-mechanical, CRT, etc.); other functional modes desired; compatibility with other aircraft mission display requirements; display location and integration into cockpit; and interface requirements in an aircraft/carrier environment. Ultimately the data will form the basis for specification of a prototype predictor display which could be installed into an aircraft for flight evaluation.

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APPENDIX

APPENDIX

SECTION 1. D & A VERSION

Mathematical derivation and circuit diagram for real time, fast time predictor models and display generation for F4-B aircraft in landing configuration used in the Dunlap and Associates, Inc. laboratory.

Basic Numerical Data for F4-B model
(REAL AND FAST TIME)

Assuming An Ideal Glide Slope

Carrier velocity = 35 knts. = 58.4 ft/sec (North)

Aircraft Data

$V = 135$ knts $= 228$ ft/sec (North) $\quad V^2 = 5.1 \times 10^4$ ft^2/sec^2

α_W (APC) $= 12.5°$ $\quad \alpha_B = 11.5°$ (1° diff. between Body and wind axes)

$\theta_0 = 8°$ (ideal glide slope of 3.5°)

$V_{XB_0} = 228 \cos 11.5° = 223.5$ ft/sec

$V_{ZB_0} = 228 \sin 11.5° = 45.5$ ft/sec

$S = 538.34$ ft^2 $\quad b = 38.4$ ft. $\quad \bar{c} = 16.04$ ft.

$m = 1055.9$ slugs $\quad I_{xx} = 24{,}660$ slug-ft^2

$I_{yy} = 120{,}123$ slug-ft^2 $\quad I_{zz} = 136{,}612$ slug-ft^2

For pattern altitude $\rho = \rho_0 = 2.35 \times 10^{-3}$ slug/ft^3

Aerodynamic Coefficients (Lumped constants)

$C_D = -0.225$

$C_{L_0} = -0.325$

$C_{L\alpha} = -3.237$ /rad

$C_{L\delta E} = 0.0066$ /deg

$C_{m_0} = -0.077$

$C_{m\alpha} = -0.24$ /rad

$C_{m\delta E} = 0.0082$ /deg

$C_{mQ} = -2.606$ /rad/sec

$C_{\ell\delta A} = 7.259 \times 10^{-4}$ /deg

$C_{\ell\delta R} = -2.138 \times 10^{-4}$ /deg

$C_{\ell P} = -0.2247$ /rad/sec

$C_{n\delta R} = 1.368 \times 10^{-3}$ /deg

$C_{nR} = -0.2268$ /rad/sec

ARI Authority

$\delta R = 1.5° / \delta A$ stick°

$\delta A = 3° / \delta A$ stick°

$\delta R = 0.5\,\delta A$

$\delta E = 0.973° / \delta E$ stick°

Stick force $\simeq 5$ lbs/deg

Variable Scaling

(Assumes a 50 volt reference)
(also assumes a non-pilot)

Variable	Maximum Value	Scaled Variable
V_{x_B}	250 fps	$[0.2 V_{x_B}]$
V_{z_B}	125 fps	$[0.4 V_{z_B}]$
T	16,000 lbs	$[3.125 \times 10^{-3} T]$
C_L	1.25	$[40 C_L]$
α	0.5 rad	$[100 \alpha]$
Q	0.5 rad/sec	$[100 Q]$
C_m		
$\dot{\theta}$	0.5 rad/sec	$[100 \dot{\theta}]$
θ		
P	1 rad/sec	$[50 P]$
R	1 rad/sec	$[50 R]$
$\dot{\psi}$	1 rad/sec	$[50 \dot{\psi}]$
ψ	50 deg	$[\psi]$
$\dot{\phi}$	1 rad/sec	$[50 \dot{\phi}]$
ϕ	50 deg	$[\phi]$
V_{x_I}	250 fps	$[0.2 V_{x_I}]$
V_{y_I}	250 fps	$[0.2 V_{y_I}]$
V_{z_I}	250 fps	$[0.2 V_{z_I}]$
δA	30 deg	$[1.67 \delta A]$
δE	20 deg	$[2.5 \delta E]$

Derived Data

$$K_1 = \frac{\rho_0 S V^2}{2} = 3.225 \times 10^4$$

$$K_2 = \frac{K_1}{m} = 30.54$$

$$K_3 = \frac{K_1 \bar{c}}{I_{yy}} = 4.306$$

$$K_4 = \frac{\rho_0 S \bar{c}^2 V}{4 I_{yy}} = 0.1544$$

$$K_5 = \frac{K_1 b}{I_{xx}} = 50.22$$

$$K_6 = \frac{K_1 b}{I_{zz}} = 9.065$$

$$K_7 = \frac{\rho_0 S b^2 V}{4} = 1.063 \times 10^5$$

$$K_8 = \frac{K_7}{I_{xx}} = 4.312$$

$$K_9 = \frac{K_7}{I_{zz}} = 0.7783$$

Scaled Equations

$$V_{xB} = \int \left[-Q V_{zB} - g \sin\theta + \frac{T}{m} + K_2 C_D \right] dt$$

$$[0.2 V_{xB}] = \int \left[- \frac{0.2 [100Q][0.4 V_{zB}] 50}{100 \times 0.4 \times \boxed{50}} - \frac{0.2 \times 32.2 [50 \sin\theta]}{50} \right.$$

$$\left. + \frac{0.2 [3.125 \times 10^{-3} T]}{3.125 \times 10^{-3} \times 1.056 \times 10^3} - 0.2 \times 30.54 \times 0.225 \right] dt$$

$$[0.2 V_{xB}] = \int \left[- 0.25 \frac{[100Q][0.4 V_{zB}]}{\boxed{50}} - 0.1288 [50 \sin\theta] + 0.0607 [3.125 \times 10^{-3} T] \right.$$

$$\left. - 1.374 \right] dt$$

$$V_{zB} = \int\left[Q V_{xB} + g \cos\theta + K_2 C_D \right] dt$$

$$[0.4 V_{zB}] = \int\left[\frac{0.4 [100 Q][0.2 V_{xB}]\, 50}{100 \times 0.2 \;\boxed{50}} + \frac{0.4 \times 32.2 [50 \cos\theta]}{50} + \frac{0.4 \times 30.54 [40 C_L]}{40} \right] dt$$

$$[0.4 V_{zB}] = \int\left[\frac{[100 Q][0.2 V_{xB}]}{\boxed{50}} + 0.269 [50 \cos\theta] + 0.3054 [40 C_L] \right] dt$$

$$C_L = C_{L_0} + \alpha_w C_{L_\alpha} + \delta E\, C_{L_{\delta E}}$$

$$[40 C_L] = 40(-0.325) + \frac{[100 \alpha_w](-3.237)\, 40}{100} + \frac{40 [2.5 \delta E][0.0066)}{2.5}$$

$$[40 C_L] = -13.0 - 1.3 [100 \alpha_w] + 0.1135 [2.5 \delta E]$$

$$Q = \int\left[K_3 C_m + K_4 Q\, C_{m_Q} \right] dt$$

$$[100 Q] = \int\left[\frac{100 \times 4.306 [500 C_m]}{500} + \frac{100 \times 0.1544 [100 Q](-2.606)}{100} \right] dt$$

$$[100 Q] = \int\left[0.862 [500 C_m] - 0.402 [100 Q] \right] dt$$

$$C_m = C_{m_0} + \alpha_w C_{m_\alpha} + \delta E\, C_{m_{\delta E}}$$

$$[500 C_m] = 500(-0.077) + \frac{500 [100 \alpha_w](-0.24)}{100} + \frac{500 [2.5 \delta E][0.0082]}{2.5}$$

$$[500 C_m] = -38.5 - 1.2 [100 \alpha_w] + 1.64 [2.5 \delta E]$$

$$\alpha_w = \alpha_B + 1^\circ = \frac{V_{zB}}{V_{xB}} + 0.01745$$

$$[100 \alpha_w] = \frac{100 \cdot 0.2 [0.4 V_{zB}]\; \boxed{50}}{0.4\; [0.2 V_{xB}]\; 50} + 1.745 = \frac{[0.4 V_{zB}]\; \boxed{50}}{[0.2 V_{xB}]} + 1.745$$

$$P = \int \left[K_5 \left(C_{l\delta A} + 0.5\, C_{l\delta_R} \right) \delta A + K_8\, P\, C_{lP} \right] dt$$

$$[50P] = \int \left[\frac{50 \times 50.22 \left(6.19 \times 10^{-4}\right) [1.67\, \delta A]}{1.67} + \frac{50 \times 4.312\, [50P] (-0.2247)}{50} \right] dt$$

$$[50P] = \int \left[0.932\, [1.67\, \delta A] - 0.97\, [50P] \right] dt$$

$$R = \int \left[K_6 \times 0.5\, \delta A\, C_{n\delta_R} + K_9\, R\, C_{nR} \right] dt$$

$$[50R] = \int \left[\frac{50 \times 9.065 \times 0.5\, [1.67\, \delta A]\; 1.368 \times 10^{-2}}{1.67} + \frac{50 \times 0.7785\, [50R] (-0.2268)}{50} \right] dt$$

$$[50R] = \int \left[0.1858\, [1.67\, \delta A] - 0.177\, [50R] \right] dt$$

Partially Scaled Equations

In these equations the parameters λ_i will be determined by your particular needs. All angles and angular rates are expressed in radians. If you convert to degrees don't forget the factor of 53.7 deg/rad.

$$[100\, \dot{\theta}] = [100\, Q] \qquad [\lambda_1 \theta] = \int \frac{\lambda_1 [100 Q]}{100}\, dt$$

$$[50\, \dot{\phi}] = [50\, P] \qquad [\lambda_2 \phi] = \int \frac{\lambda_2 [50 P]}{50}\, dt$$

$$[50\, \dot{\psi}] = [50 R] + \frac{50 \times 0.145\, [\lambda_2 \phi]}{\lambda_2}$$

$$[\lambda_3 \psi] = \int \left[\frac{\lambda_3 [50R]}{50} + \frac{\lambda_3 \times 50 \times 0.145\, [\lambda_2 \phi]}{\lambda_2^2} \right] dt$$

$$[0.2\, V_{x_I}] = \frac{[0.2\, V_{x_B}][50 \cos\theta]}{\boxed{50}} + 0.91\, [50 \sin\theta] \qquad \text{(Assumes } V_{z_B} \sim 45.5 \text{ fps)}$$

$$[0.2\, V_{z_I}] = -\frac{[0.2\, V_{x_B}][50 \sin\theta]}{\boxed{50}} + \frac{0.5\, [0.4\, V_{z_B}][50 \cos\theta]}{\boxed{50}}$$

$$[0.2\, V_{y_I}] \cong 0.447\, [100\, \psi] \qquad \text{assumes } \psi_{max} = 0.5 \text{ rad} \quad \text{(only good for } \psi \text{ in rad.)}$$

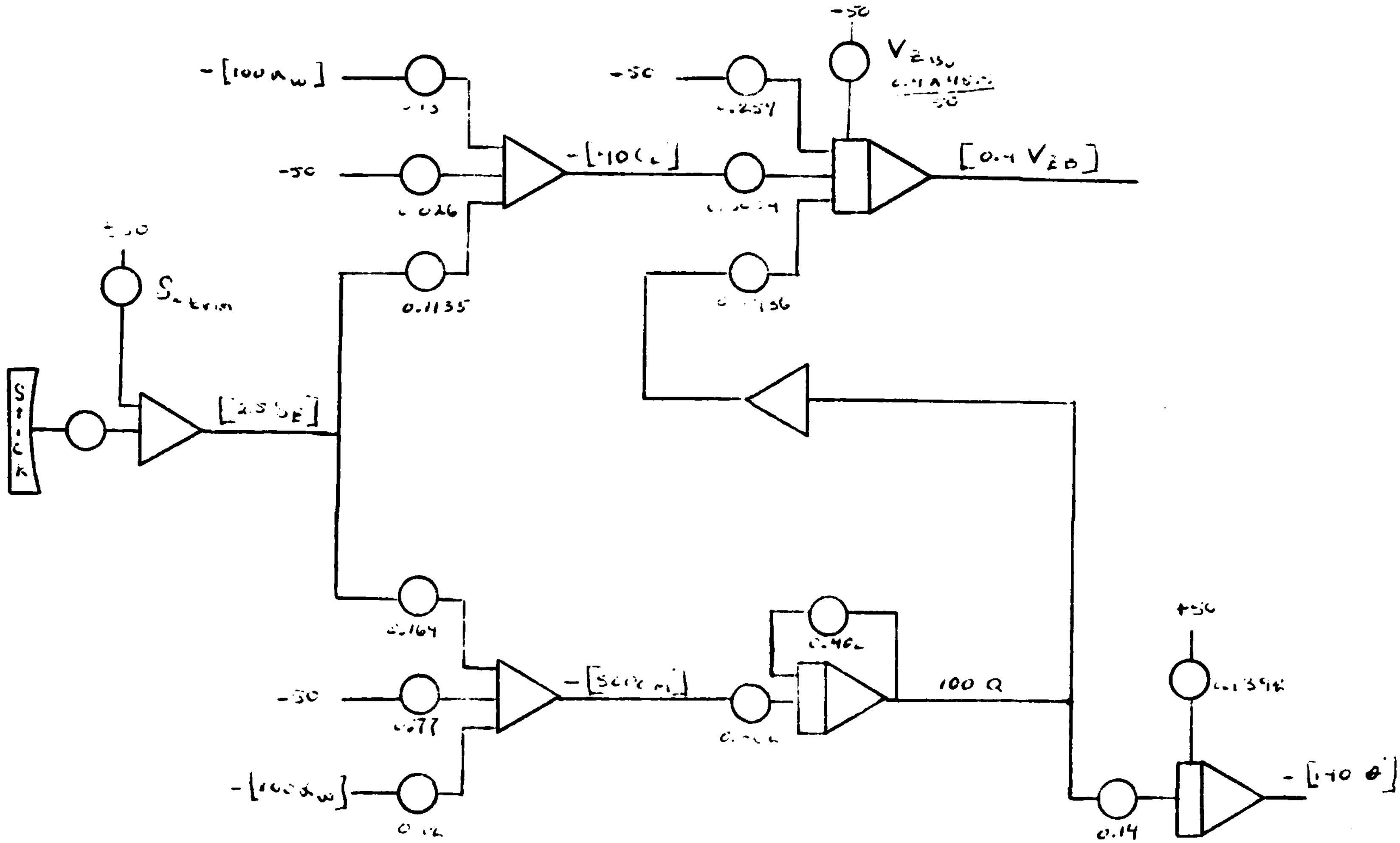


Figure 1. Real time F4-B landing model circuit diagram (D&A lab version)

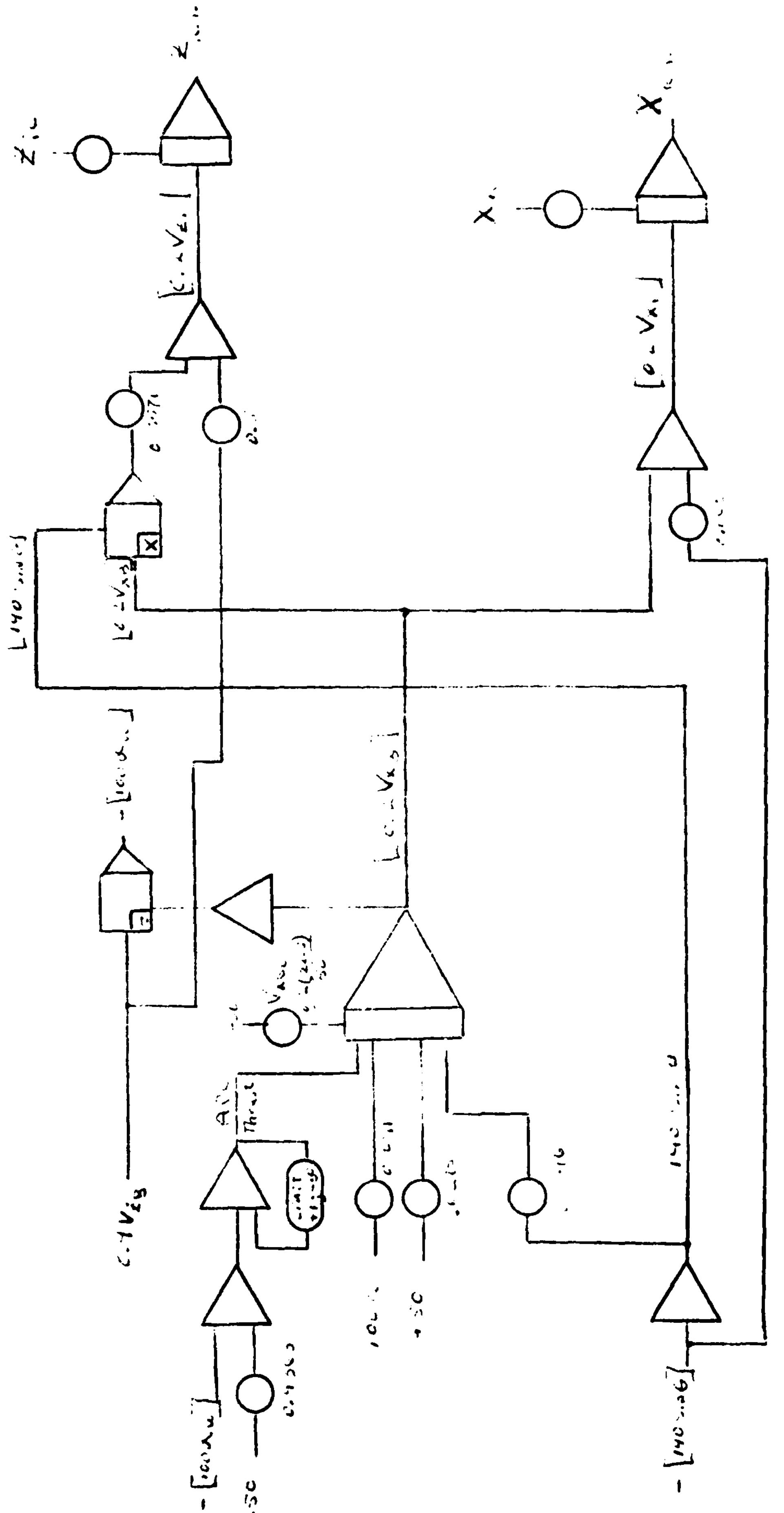


Figure 1 (Continued)

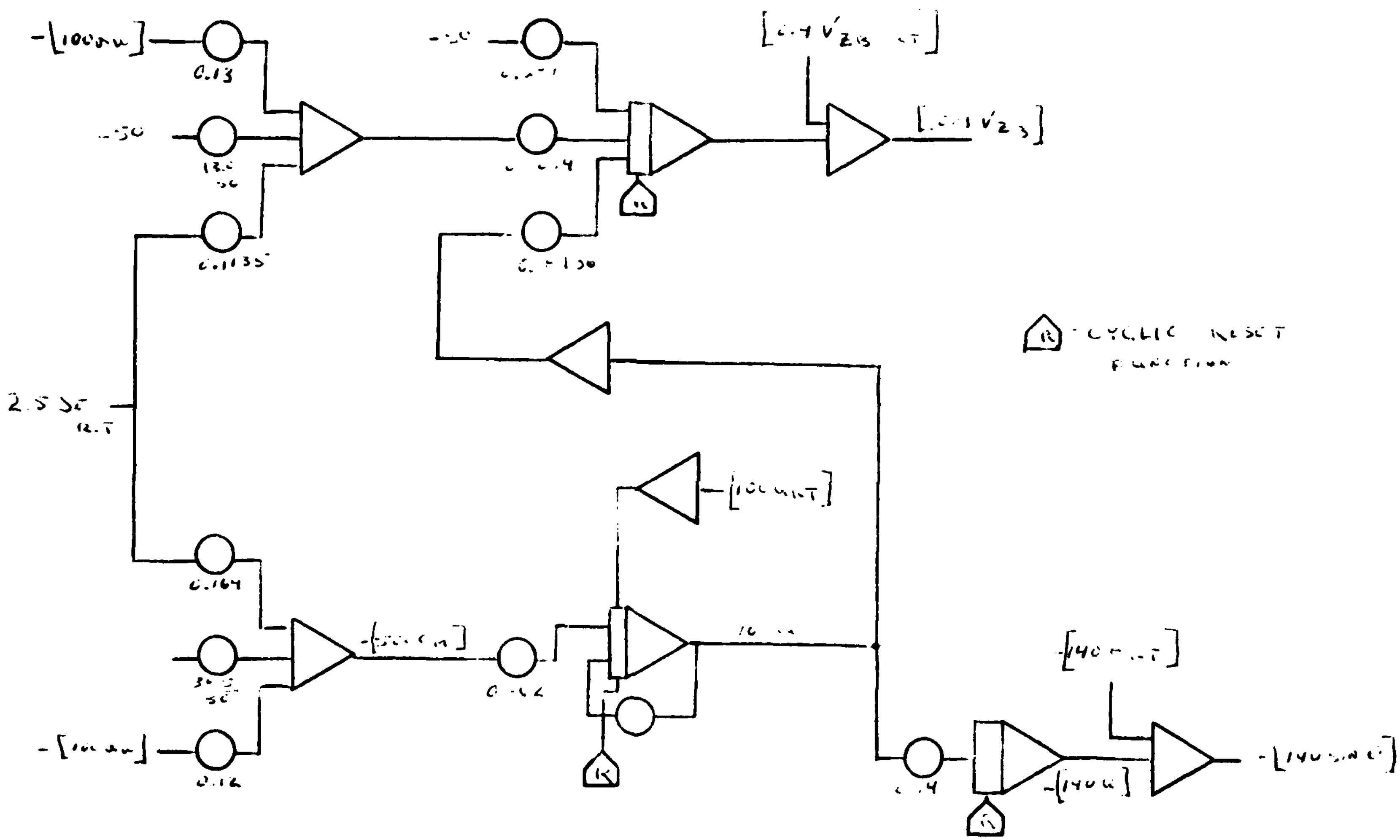


Figure 2. Fast time F4-B landing model predictor circuits (D&A lab version)

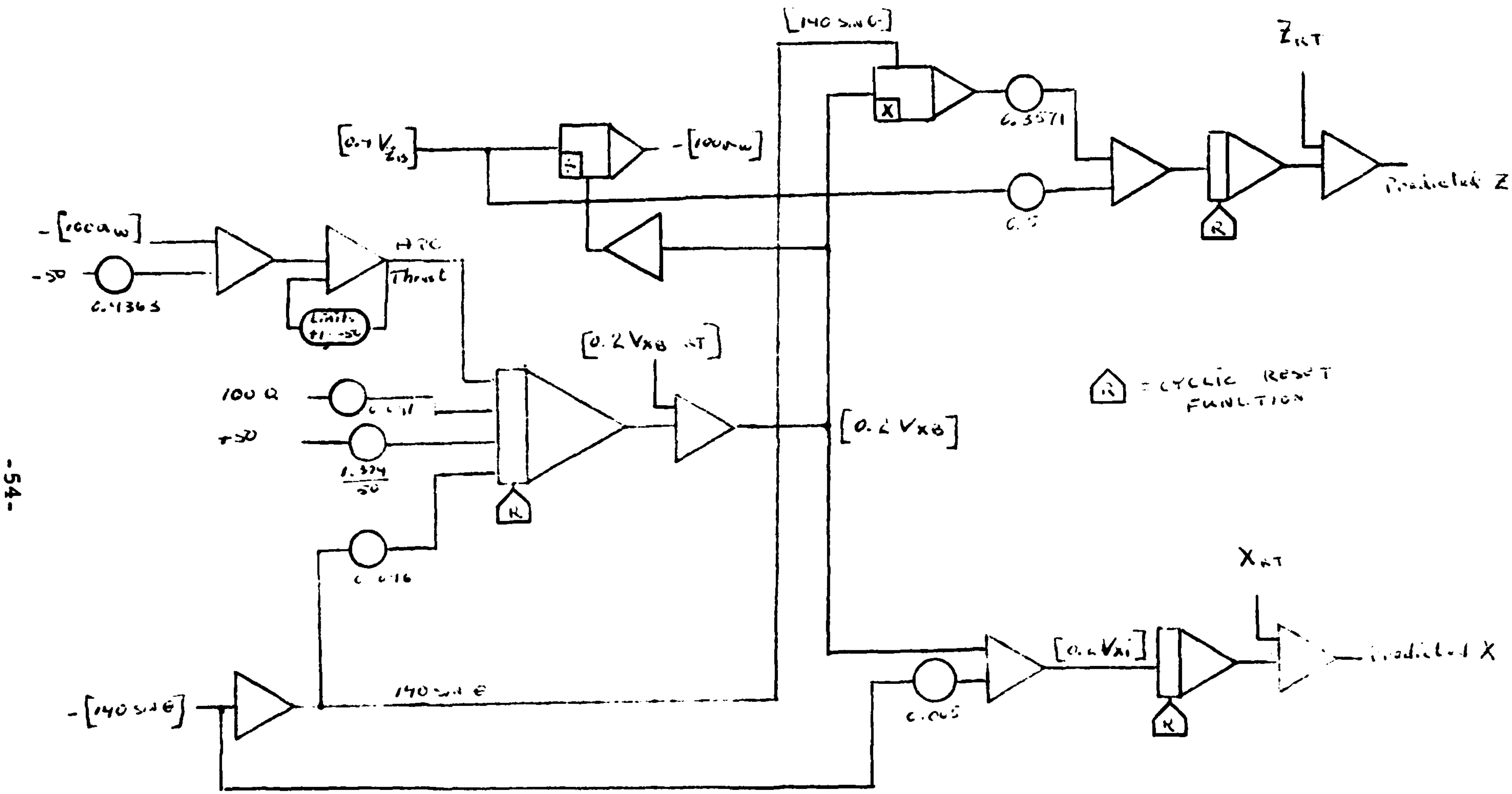
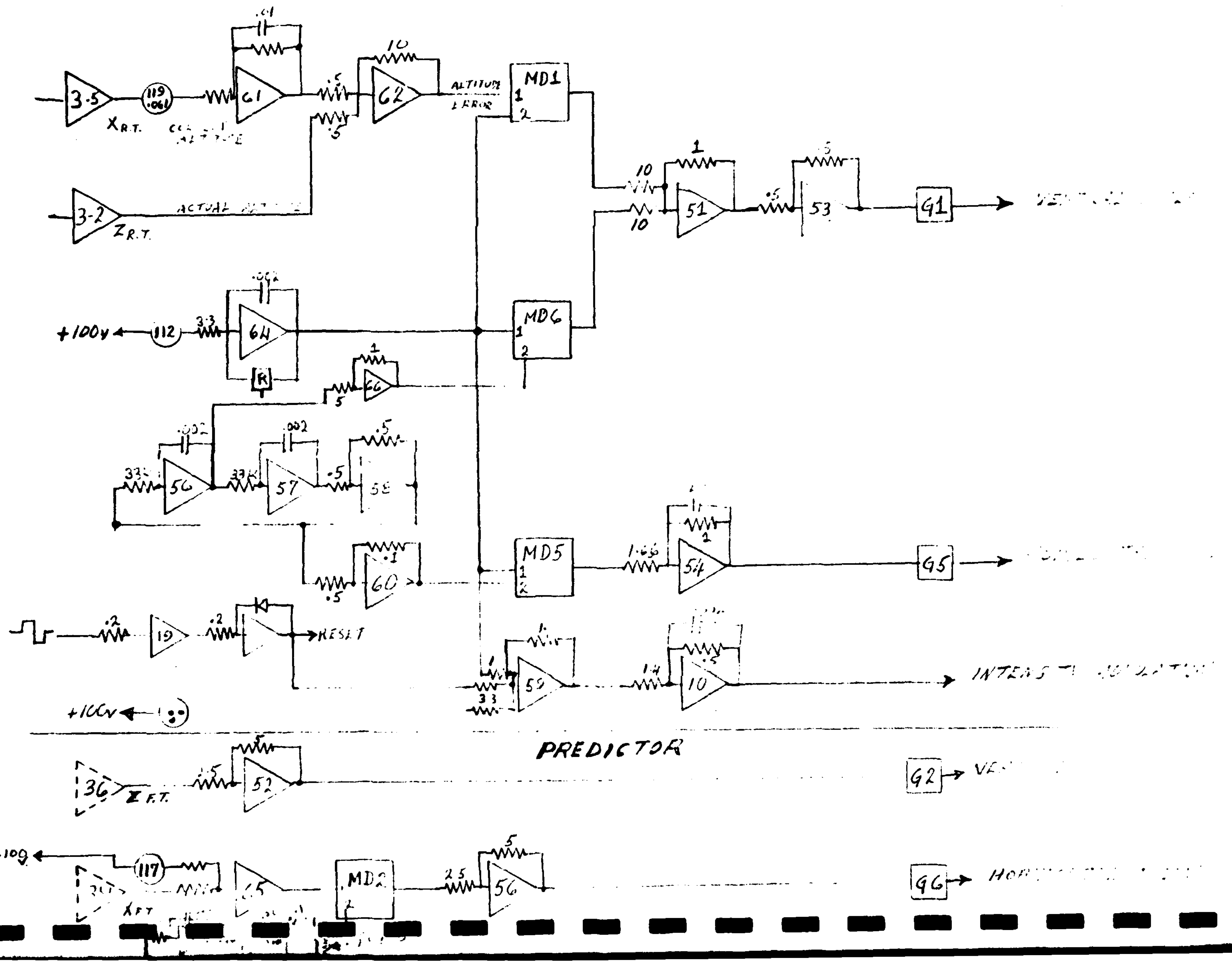


Figure 2 (Continued)

Glideslope reference and display symbology generation (D&A lab version)



APPENDIX

SECTION 2. PT. MUGU VERSION

Mathematical derivations and circuit diagrams for F4-B fast time predictor model, glide slope reference and display generation used in Phase A demonstration at Pt. Mugu Naval Research and Test Center.

BASIC NUMERICAL DATA FOR FA[illegible] TI[illegible] F[illegible] M[illegible]L

$\rho_0 = 2.35 \times 10^{-3}$ $S = [illegible]$ $\bar{c} = 16.04$ $V = 233$

$m = 1055.9$ $I_{max} = 16{,}000$ $I_{yy} = 120{,}123$

[illegible] : [illegible]

$\Gamma_m = 1515$

$\frac{\rho_0 S V_\cdot}{2} = [illegible] \times 10^{[illegible]}$

$\rho_0 S \frac{V^2}{2} = 3.11561 \times 10^{1}$

$\frac{\rho_0 S V_\cdot^2}{2 m} = 2.4711 \times 10^{1}$

$\frac{[illegible]\, \bar{c}}{[illegible]\, I_{yy}} = 4.2$

$\frac{\rho_0 S \bar{c}^2 V_\cdot}{4 \cdot I_{yy}} = 0.151061$

$\frac{\rho_0 S \bar{c}^2 V_\cdot}{4 \cdot I_{yy}} C_{m_Q} = -0.3737$

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
V_{x_0}	250 fps	$[2.4\, V_{x_0}]$			
V_{z_0}	30 fps	$[[illegible]\, V_{z_0}]$			
Q	0.5 rad/sec	$[200\, Q]$			
θ	π rad	$[[illegible]\, \theta]$			
C_D	0.214	$[[illegible]\, C_D]$			
C_L	1.0	$[100\, C_L]$			
C_m	0.167	$[600\, C_m]$			
α	18.35°	$[312.5\alpha]_{rad}$			
V_{x_E}	2[illegible]0 fps	$[[illegible]\, V_{x_E}]$			
V_{z_E}	[illegible] fps	$[[illegible]\, V_{z_E}]$			

$$V_{x_1} = \int \left(-Q V_{z_B} + b_{15}\, g + \frac{T}{m}\, \delta_T + \frac{\rho_0 S}{2m} V^2 C_D \right) dt$$

$$C_D = -0.015 + 0.03 + 0.111 - 0.1625\, C_L^2$$

$$V_{z_B} = \int \left(Q V_{x_B} + b_{33}\, g + \frac{\rho_0 S}{2m} V^2 C_L \right) dt$$

$$C_L = -3.2875\, \alpha + 0.0066\, \delta_E - 0.34 + 0.015$$

$$Q = \int \left(\frac{\rho_0 S \bar{c}}{2 I_{YY}} V^2 C_m + \frac{\rho_0 S \bar{c}^2}{4 I_{YY}} V C_{m_Q} Q \right) dt$$

$$C_m = 0.012 - 0.21\, \alpha + 0.0082\, \delta_E \doteq 0.087$$

$$C_{m_Q} = -2.6261$$

$$[0.4\,V_{33}] = \int\left(-\frac{0.4\,[\text{[illegible]}][1.25\,V_{33}]\,100}{200 \times 1.25\;\text{[illegible]}} + \frac{0.4\,[100\,b_{33}]\,(38.3}{100} + 0.4 \times 15.15\;\delta_f + 0.4 \times \text{[illegible]} \right) dt$$

$$= \int\left(\text{[illegible]}\;[1.25\,V_{33}] + \text{[illegible]}\;[100\,b_{33}] + 6.06\;\delta_f + \text{[illegible]}\;[100\,C_L] \right) dt$$

$$[340\,C_D] = 340\,(0.135) + \frac{340 \quad 0.1625\;[100\,C_L]^2\;100}{100 \times 100 \quad [\text{[illegible]}]}$$

$$= 45.9 + 30.7 + 0.\text{[illegible]}\;\frac{[100\,C_L]^2}{[\text{[illegible]}]}$$

$$[1.25\,V_{33}] = \int\left(\frac{1.25\,[\text{[illegible]}][1.25\,V_{33}]\,100}{\text{[illegible]}} + \frac{1.25\,[100\,b_{33}]\,(38.3)}{100} + \frac{1.25 \times 21.71\,[100\,C_L]}{\text{[illegible]}} \right) dt$$

$$= \int\left(1.565\,\frac{[\text{[illegible]}][1.25\,V_{33}]}{[\text{[illegible]}]} + 0.425\,[100\,b_{33}] + 0.3125\,[100\,C_L] \right) dt$$

$$[100\,C_L] = 100\,(-0.325) + \frac{100 \times 3.2373\;[312.5\,\alpha]}{312.5} + \frac{120 \times 0.0066\;[5\,\delta_E]}{5}$$

$$= -32.5 + 1.035\,[312.5\,\alpha] + 0.132\,[5\,\delta_E]$$

$$[200\,Q] = \int\left(\frac{200 \times 4.2\,[600\,C_m]}{600} - \frac{200 \times 0.3137\,[200\,Q]}{200} \right) dt$$

$$= \int\left(1.4\,[600\,C_m] - 0.3137\,[200\,Q] \right) dt$$

$$[600\,C_m] = 660\,(-0.07) - \frac{600 \times 0.21\,[312.5\,\alpha]}{312.5} + \frac{600 \times 0.0088\,[5.5\,E]}{5}$$

$$= -46.2 - 0.404\,[312.5\,\alpha] + 1.057\,[5.5\,E]$$

$$[31.83\,\Theta] = \int \frac{31.83\,[200\,Q]}{200}\,dt = \int 0.1592\,[200\,Q]\,dt$$

$$[312.5\,\alpha] = \frac{312.5}{1.25}\,\frac{[1.25\,V_{2B}]\,\boxed{Bc} \times 0.4}{[0.4\,V_{XB}]\;100} = \frac{[1.25\,V_{2B}]\,\boxed{Bc}}{[0.4\,V_{XB}]}$$

$$[0.4\,V_{XL}] = \frac{0.4\,[0.4\,V_{XL}][100\cos\theta]\,100}{0.4\times 100\;[100]} + \frac{0.4\,[1.25\,V_{XL}][100\sin\theta]\,100}{1.25\times 100\;[100]}$$

$$= \frac{[0.4\,V_{XL}][100\cos\theta]}{[100]} + 0.3333\,\frac{[1.25\,V_{XL}][100\sin\theta]}{[100]}$$

$$[2\,V_{2L}] = \frac{2\,[1.25\,V_{XL}][100\cos\theta]\,100}{1.25\times 100\;[100]} - \frac{2\,[0.4\,V_{XL}][100\sin\theta]\,100}{0.4\times 100\;[100]}$$

$$= 1.6\,\frac{[1.25\,V_{XL}][100\cos\theta]}{[100]} - 5.0\,\frac{[0.4\,V_{XL}][100\sin\theta]}{[100]}$$

$$\left[100\left(1-\frac{2X}{X_1}\right)\right] = 100 - \frac{2}{10^3}\int\frac{[0.4\,V_{XL}]}{0.4}\,dt$$

$$= 100 - 0.005\int[0.4\,V_{XL}]\,dt$$

$$\left[100\left(1-\frac{Z}{Z_{in}}\right)\right] = 100 - \frac{200}{10^3}\int\frac{[2\,V_{2L}]}{2}\,dt$$

$$= 100 - 0.1\int[2\,V_{2L}]\,dt$$

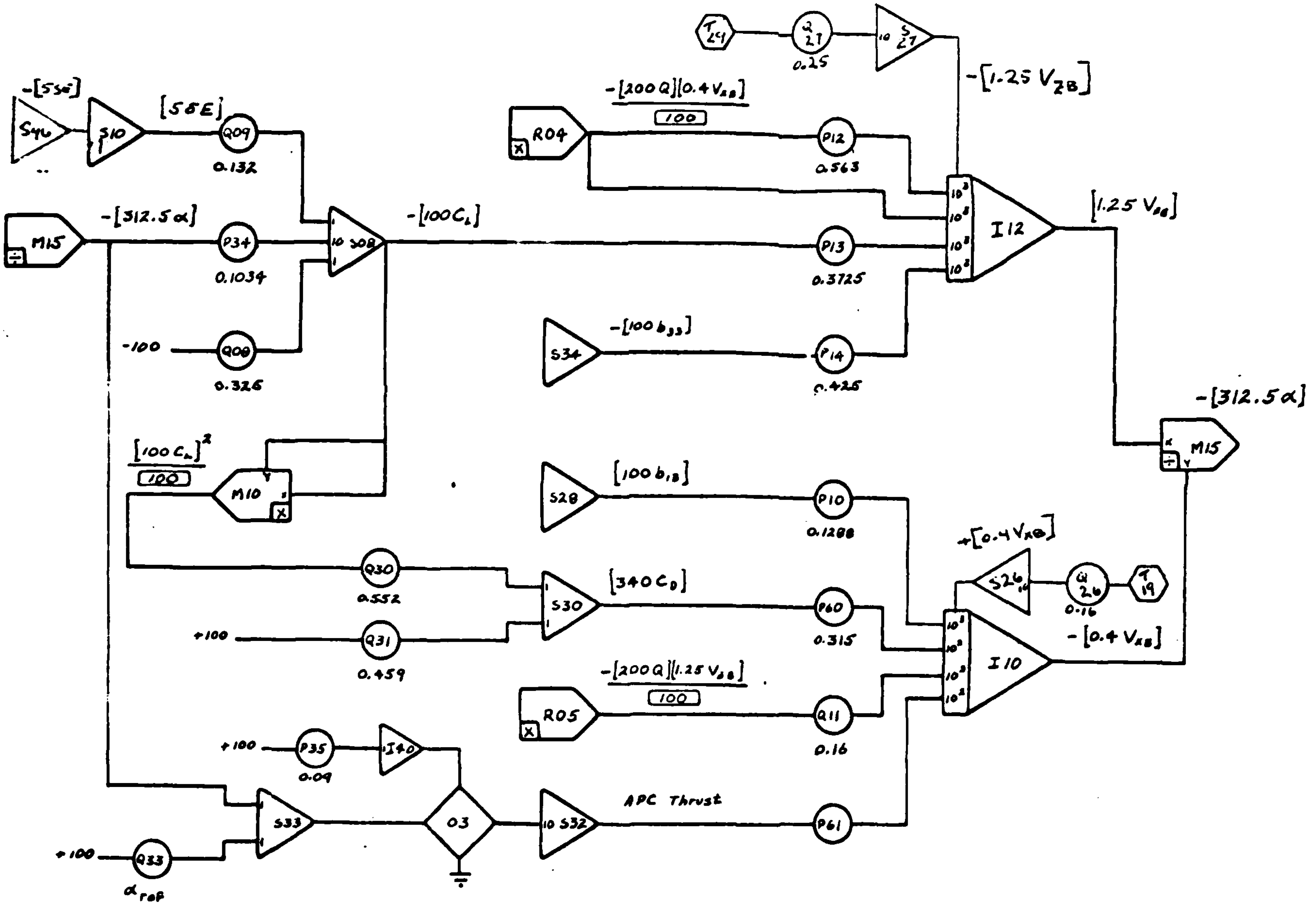


Figure 1. F4-B Fast time model predictor circuits

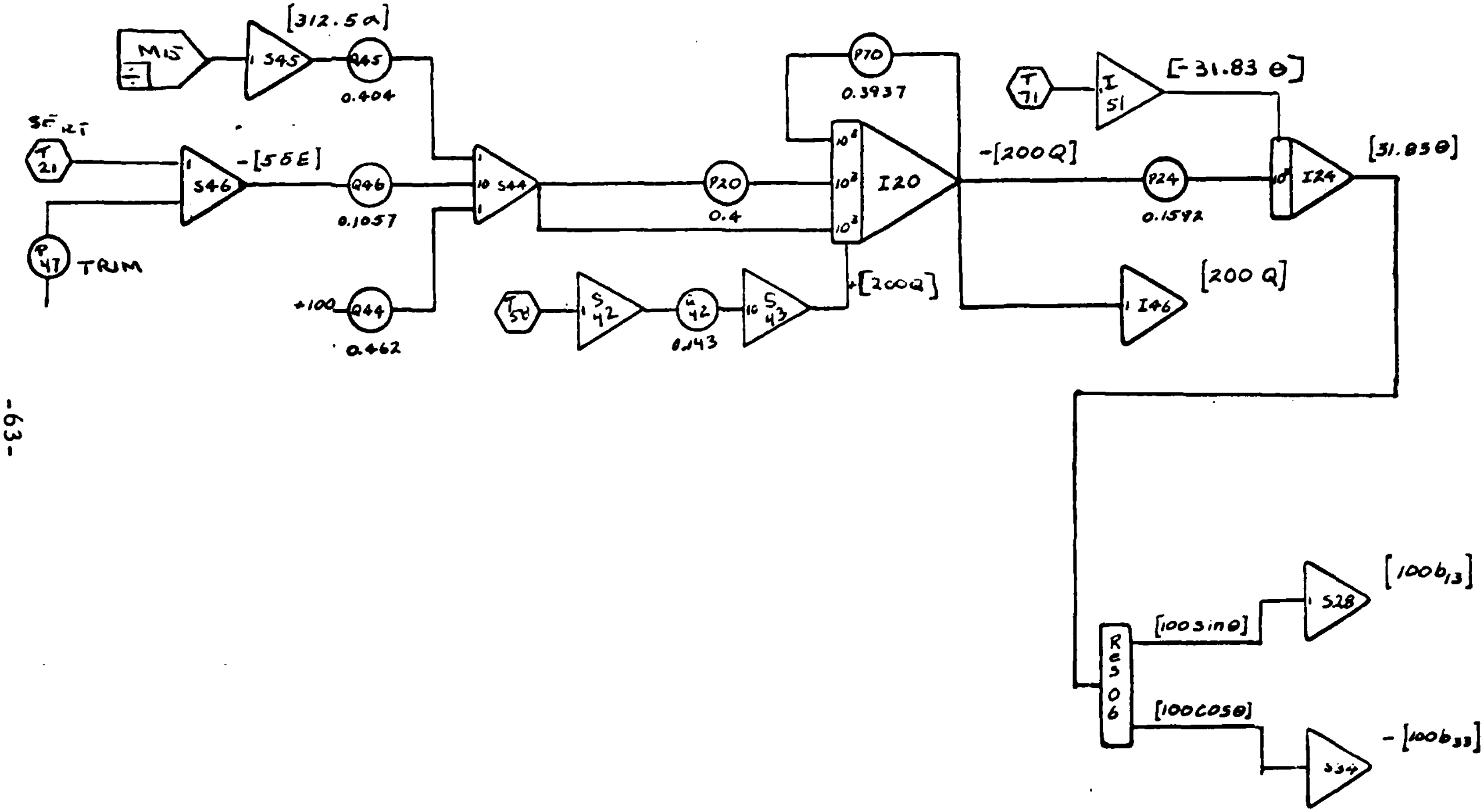


Figure 1. (continued)

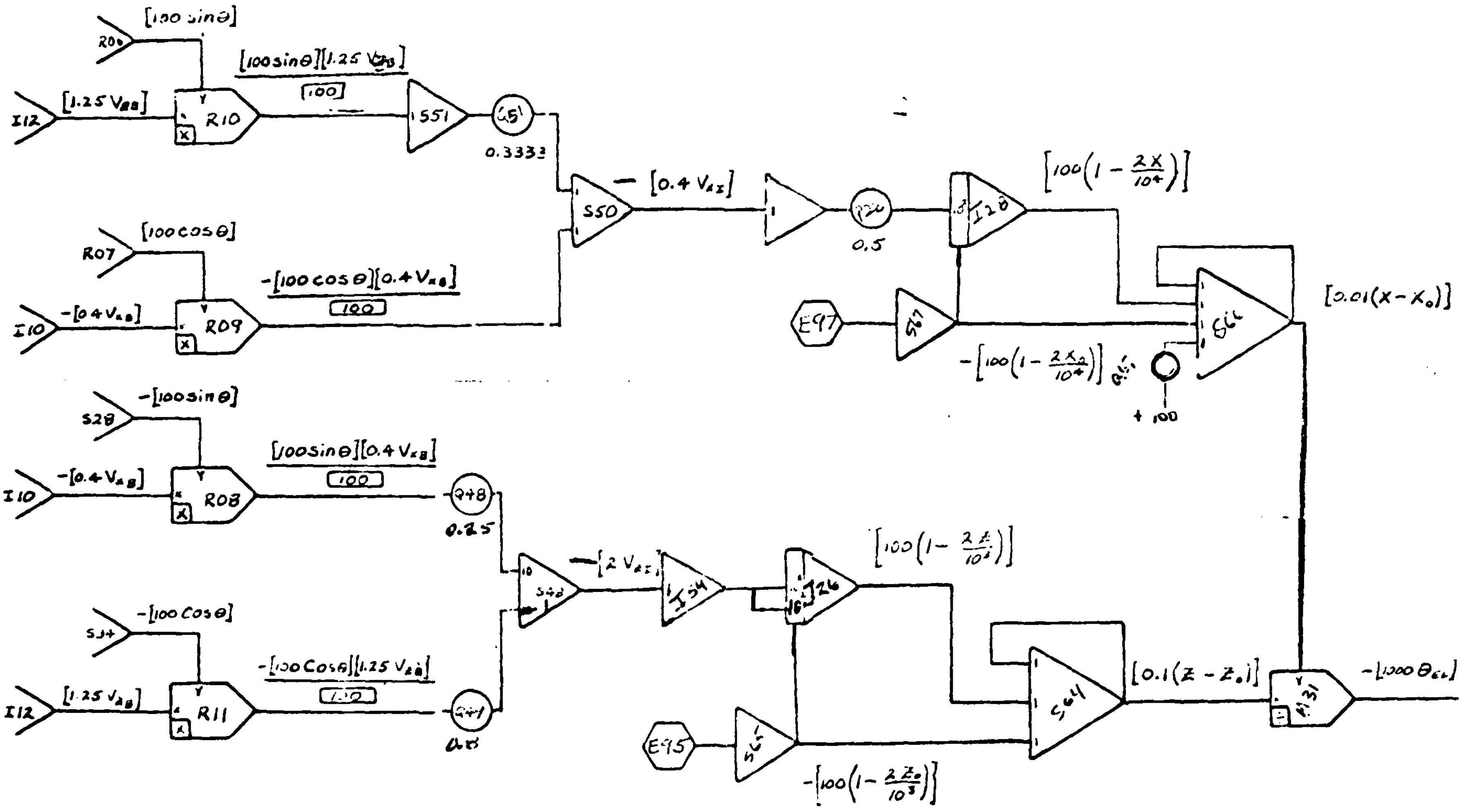


Figure 1. (continued)

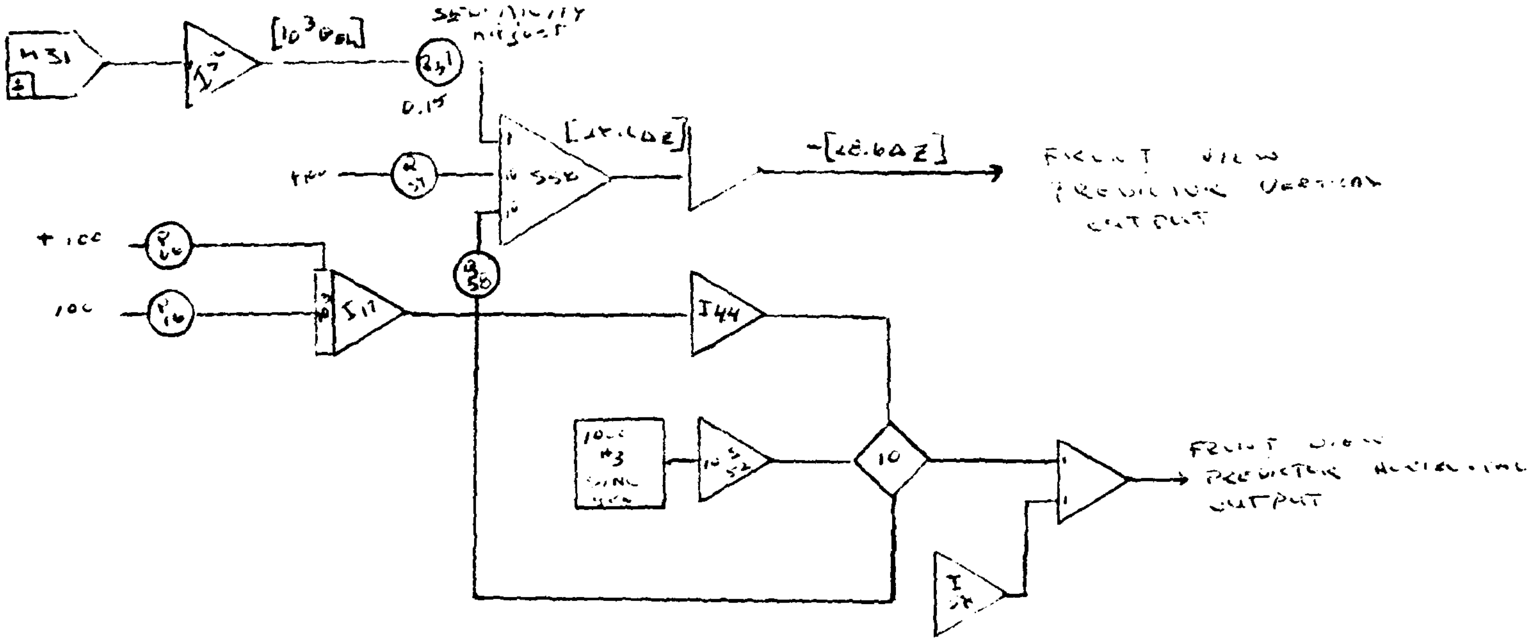


Figure 2. Front view display generation circuits

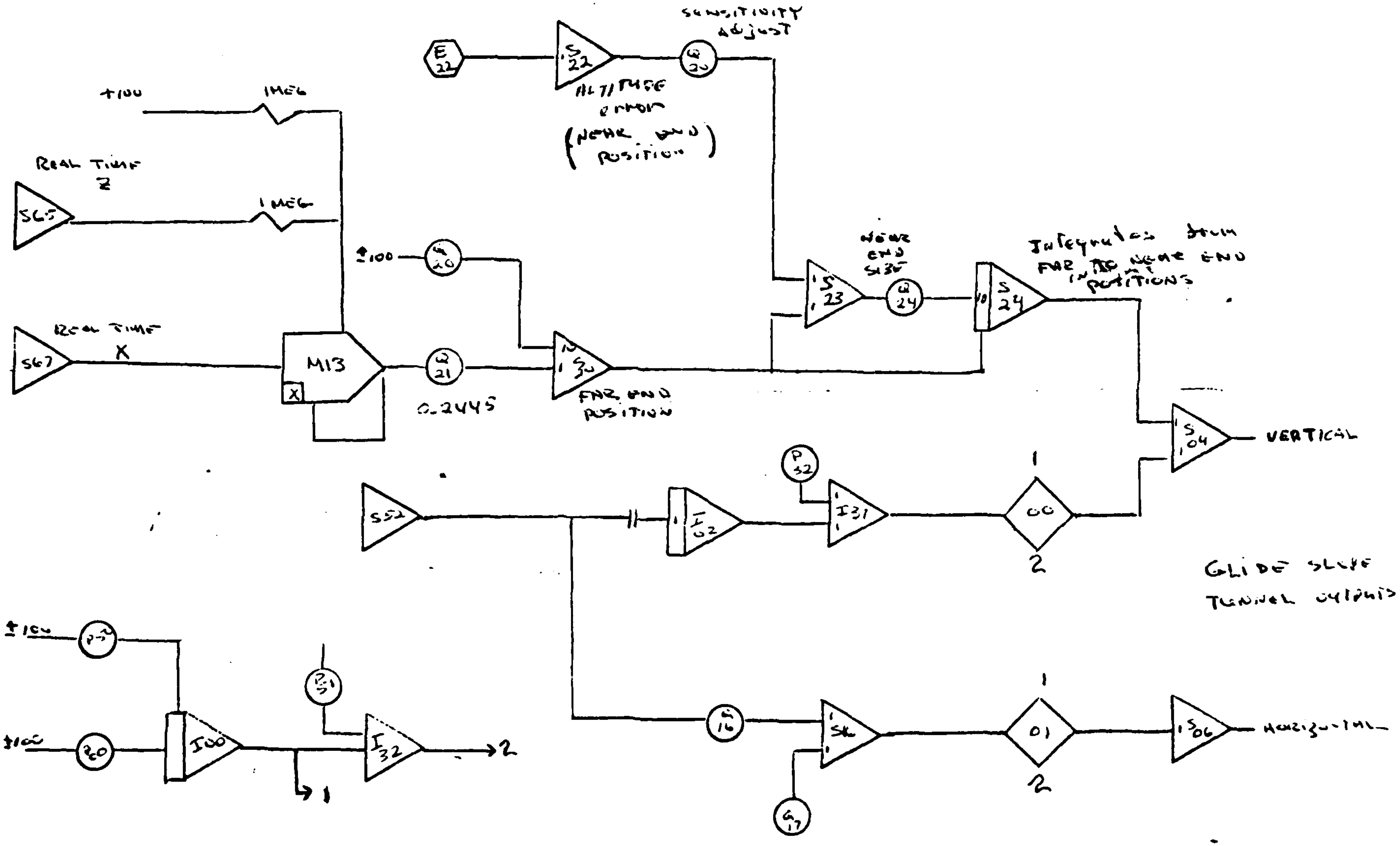


Figure 3. Glide slope reference computation and display circuits

APPENDIX

Section 3

SHIP MOTION MODEL

SHIP MOTION PREDICTION

INTRODUCTION

One of the Phase A tasks was to explore a predict·· model technique for predicting ship motions. The predictor model approach is different from other approaches taken to ship motion prediction. One of the approaches taken by others requires the sensing of wave motion ahead of the ship. The approaching wave data is then operated on by mathematical functions representing the ship's reaction to the waves. The ship's reactions in turn are analyzed into specific motions of interest, such as pitch angle, heave, etc.

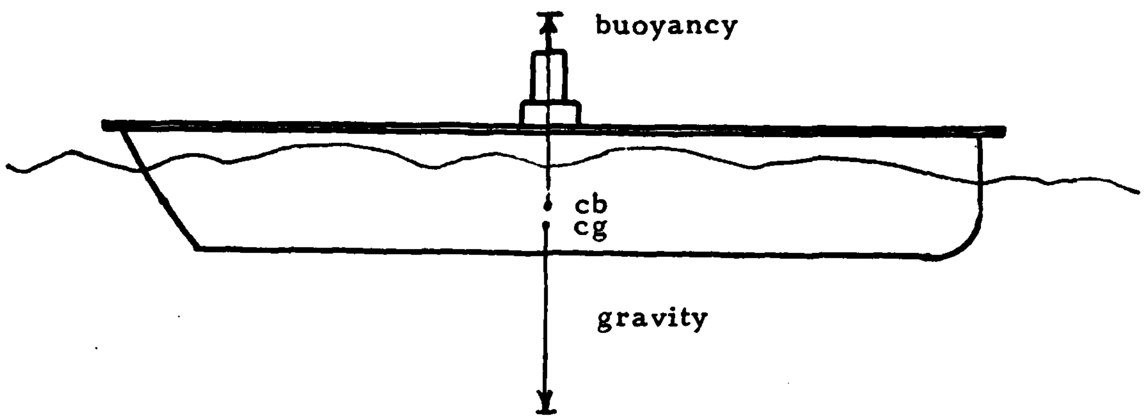
The predictor model approach taken here essentially models, in a simplified way, a combination of the wave actions which may exist at any period of time and the ship's motion in reaction to them. The discrepancy between actual ship motions and predicted motions are used to adjust the model. By adapting iteratively in this manner the ship motion model can be made to adapt to and predict ship motions.

SHIP MOTION

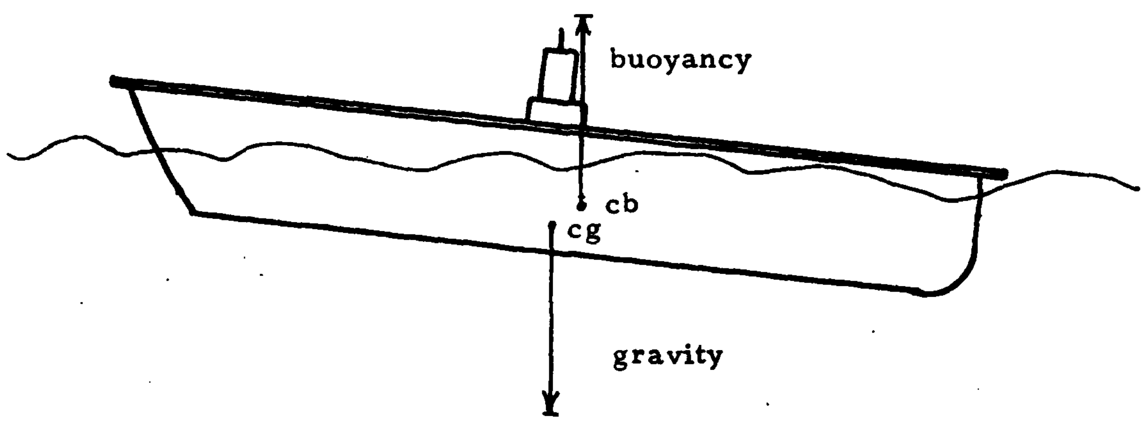
It has long been recognized that an important source of variation in carrier landing performance is ship motions. Most significant are pitch and heave motions, which can change a safe landing into a ramp strike.

A moving ship has pitch motion characteristics much like a damped pendulum excited by random disturbances. A pitching ship is, in fact, a pendulous system, because the center of gravity of the ship is below the forces of buoyancy operating at the center of buoyancy, the center of mass of the displaced water (see Figure 1). Pitch equilibrium requires that downward forces acting (in effect) at the center of gravity be vertically aligned with upward forces acting, in effect, at the center of buoyancy. This vertical alignment defines the actual zero pitch angle position of the ship, the position the vessel will settle into in smooth water when its pitch equilibrium is not disturbed. When the ship pitches, the center of buoyancy is shifted fore or aft of the center of gravity. The combination of upward forces at the center of buoyancy and downward forces at the center of gravity then produces a moment, a pitch acceleration, in the direction of restored pitch equilibrium. The effect of this process is to produce pendulous motion at the ship's natural pitch frequency. The motion is not perfectly sinusoidal because of the change in shape of that part of the ship volume below the water surface as the ship pitches, but it is close.

There is also a natural heave frequency resulting from the vertical component of the opposed forces acting at the center of buoyancy and of



a. <u>Pitch equilibrium</u>; forces of buoyancy and gravity are vertically aligned.



b. <u>Pendulosity.</u> When the ship pitches, forces due to buoyancy and gravity are no longer aligned, and a pitch acceleration acting to realign these forces is present. It is as if the center of gravity were a pendulum suspended from the center of buoyancy.

Figure 1. Natural pitch frequency which occurs as a result of pendulous motion.

gravity, respectively. This is the natural frequency of the damped vertical oscillations that would occur if the ship were lifted (or depressed) in still water to a point at which buoyancy were less than (or greater than) the ship's weight.

In addition to the motions at these natural frequencies are the components of ship motion corresponding to wave frequencies other than the natural pitch or heave frequency of the vessel (see Figure 2). These account for much and probably most of the variance in ramp height above mean sea level in the carrier landing situation. Some amount of this motion is also predictable over short intervals, although the problem is more difficult than prediction at the natural frequencies.

APPROACH TO SHIP MOTION PREDICTION

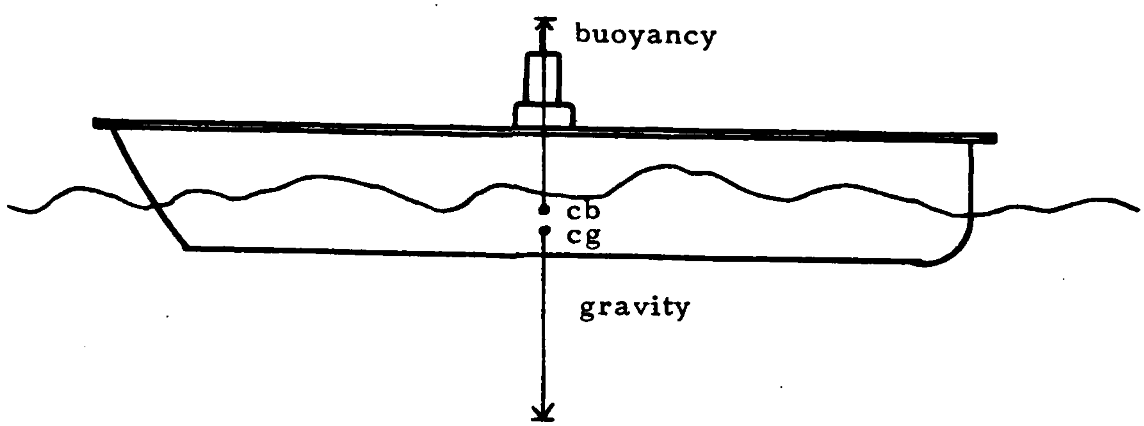
A task of this study was to investigate the ship motion problem in relation to developing a fast-time predictor model of ship motions, the output of which could be used in a number of ways, including incorporation into the carrier landing predictor display. It was impossible, within the scope of this contract, to conduct either a major mathematical or empirical study of the ship motion prediction problem. Instead, a fast-time predictor model that might provide a useful degree of ship motion prediction, and that would be compatible with the aircraft trajectory prediction technique used here was developed.

Two possible forms of fast time ship motion model were considered. The first would employ a dynamic model of the ship response to wave action, through which a radar (or other instrument) scan of the waves ahead could be played in fast time to produce predicted ramp motions from present time to the number of seconds ahead in the scan signal. This is related to the technique of Kaplan and Sargent (1970) (2). The prediction could be used to generate a display for the pilot and/or LSO.

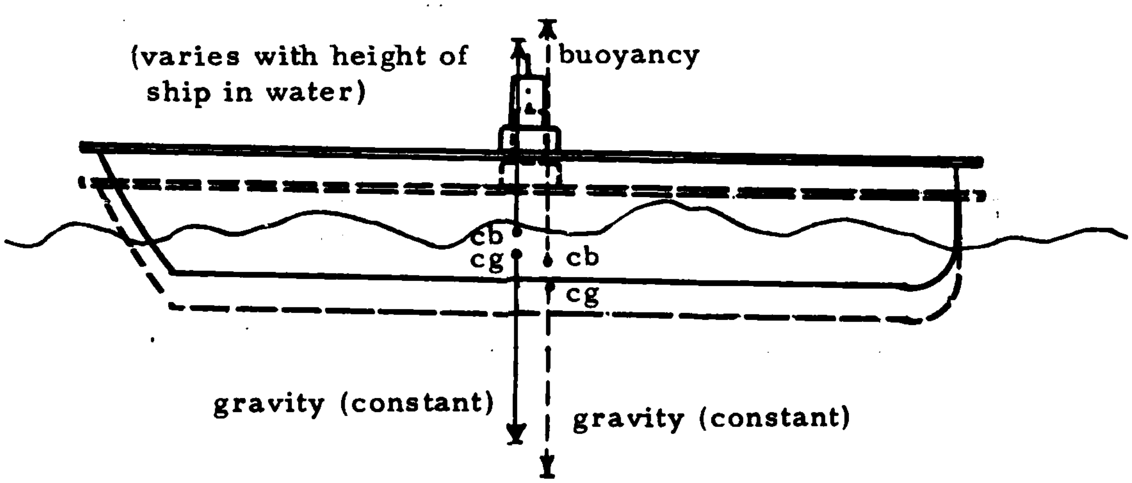
However, the technique chosen is simpler and does not depend on such a radar or other wave sensor. It is accomplished with a fast time adaptive predictive model formed by summing the outputs of two or more sine wave generators. These sine waves can be adjusted in amplitude and phase, and those not corresponding to one of the ship's natural frequencies can be adjusted in frequency. The output of the approach used can be predicted ramp or deck height over several seconds or at the predicted time of ramp crossing.

SHIP MOTION MODEL

The simplified ship motion model developed in the Dunlap laboratory employed two fixed frequency fast-time sine wave generators having the



a. Heave stability exists when forces of buoyancy and gravity are equal.



b. Heave oscillation occurs when the force of buoyancy is less or greater than that of gravity. The carrier will then bob up and down in damped oscillation at its natural frequency.

Figure 2. Natural heave frequency occurs as a result of variation in the force of buoyancy from greater to less than that of gravity; the ship bobs up or down.

special feature that they could be played either forward or backward. This meant that a time history recording of ship motion (e. g., the past 20 seconds) could be employed to cyclically update the four model parameters (amplitude and phase of two sine waves) using a model matching technique in which the model computed backward from the present instant of time. The same model with its updated parameters was then reversed in time to generate a prediction for the desired number of seconds ahead. The model as developed cycled alternately backward (adaptive cycle) and forward (prediction cycle). The level of effort allocated in this contract permitted the model to be mechanized and the feasibility of the "forward-backward" aspect of the model shown, but did not provide for model matching runs using simulated or actual ship motion signals to follow and predict.

The ship motion model output is shown in Figure 3 in concept. The upper trace is a record of the actual time history of the ramp height. It is stored and updated several times per second - perhaps at the same rate that the predictor model cycles. The lower trace shows the time history with the two model outputs. The difference between the adaptive trace and actual history forms the primary signal for adjusting the model. A criterion such as time-weighted mean square error(error weighting becomes smaller as it moves further away in time) is measured as an aid in adjusting the model parameters.

The technique of operating the predictive model backward as well as forward in time is accomplished simply by inverting the sign of the first derivative of each sine wave at the beginning of the adaptive (rather than the predictive cycle) (see Figure 4). In those sine waves generated by means of two integrators and an inverter, it is only necessary to feed the appropriate integrator with the negative of its initial condition to accomplish "backward" operation. The second derivative of the sine wave does not require inversion, so the other integrator receives the same initial condition for adaptive and predictive cycles.

The initial conditions for each integrator for each cycle of operation are obtained at the appropriate point in the previous prediction cycle. This requires that each integrator output be sampled and its value held to provide the starting values for the next cycle. The simplest way to adjust the phases of each sine wave is to change the sample point at which the sample and hold for each sine wave operates to obtain its initial condition. The other two parameters, amplitude of each of the two sine waves were adjusted by simply varying the two signal gains through a potentiometer.

The model was set up in the laboratory to demonstrate the soundness of the concept of the adaptive-predictive backward-and-forward running

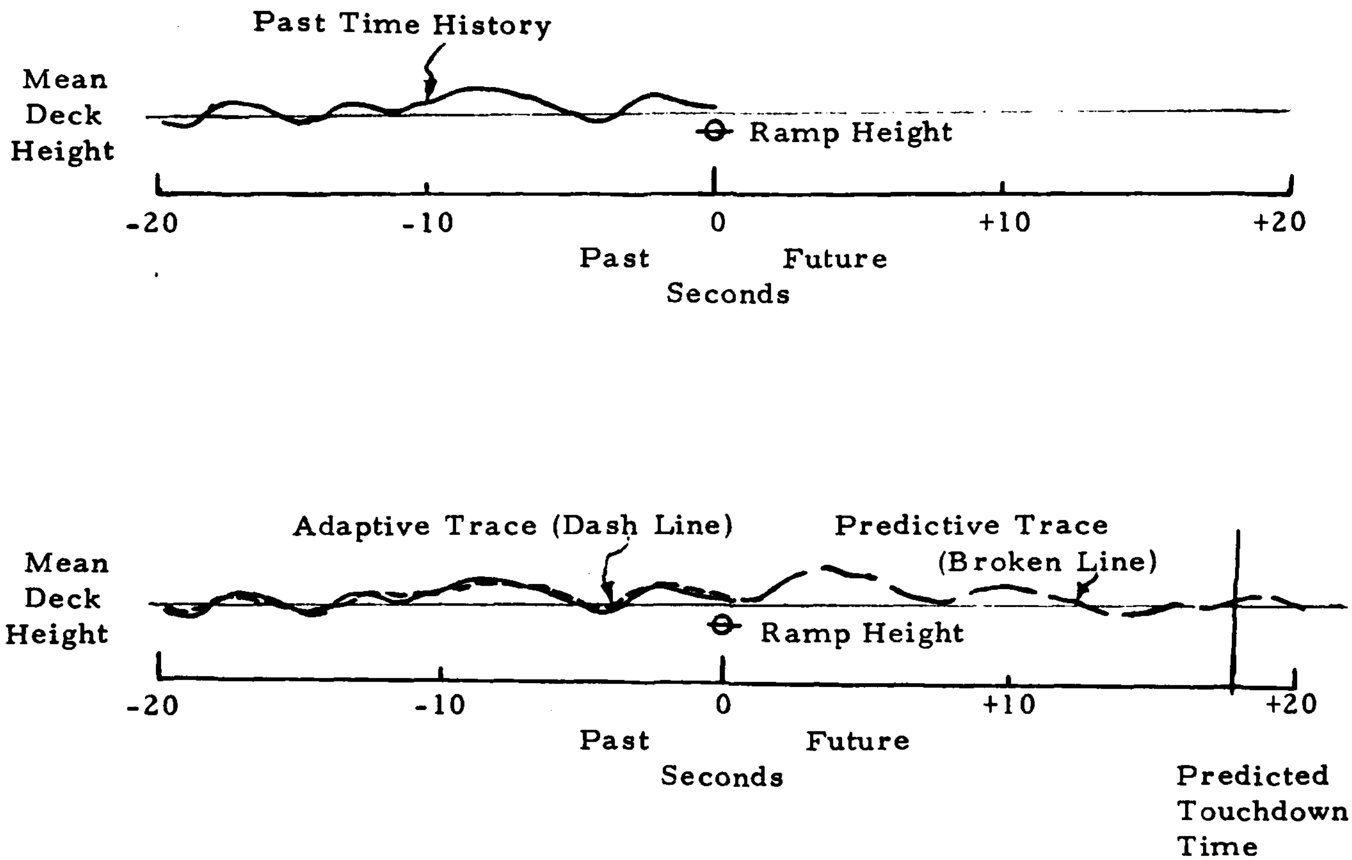


Figure 3. Ship motion model concept.

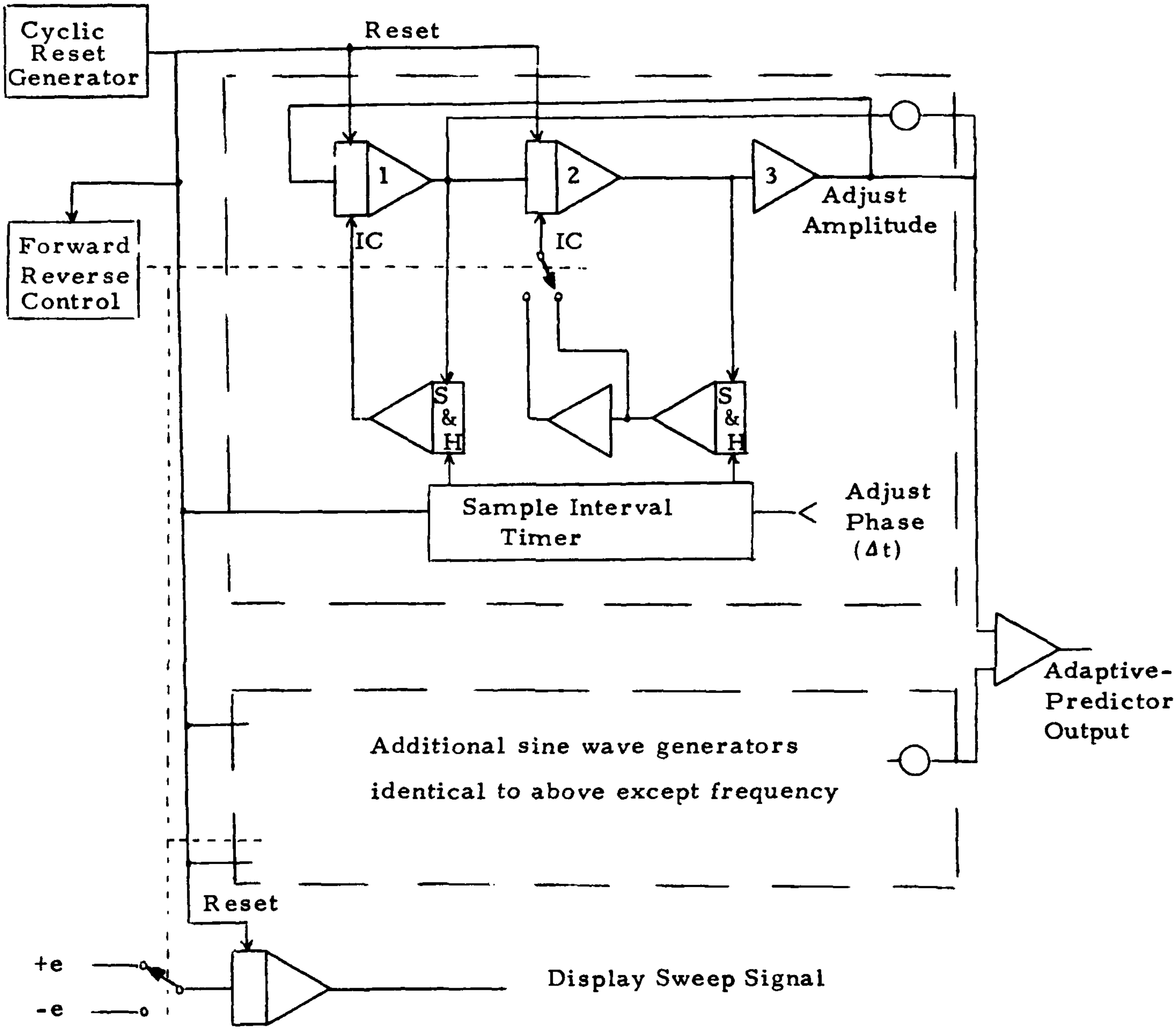


Figure 4. Block diagram of adaptive-predictive ship motion model.

fast time model. Funds were not available to carry the development of the model further. It is believed that the concept deserves further development and testing. However, the level of development reached in the present project did not merit the appliction of the ship motion prediction technique in the aircraft predictor displays of this study.

The ship motion model output trace could be used to calculate predicted touchdown altitude. This in turn could be integrated into glideslope information so that the pilot flies a glideslope which ends at a predicted rather than the actual deck height, at the predicted touchdown point. Note that the prediction is always in terms of either ramp height at crossing or deck height touchdown (see Figure 3). Note also that although the predicted deck height can be expected to change as touchdown is approached, it will change much more slowly than present deck height. The change in predicted deck height only represents the improvement in prediction that occurs as touchdown becomes closer.

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